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TECHNOLOGY SURVEY OF ELECTRICAL POWER GENERATION AND DISTRIBUTION FOR MIUS APPLICATION

hudmius

MODULAR INTEGRATED UTILITY SYSTEMS

improving community utility services by supplying electricity, heating, cooling, and water/ processing liquid and solid wastes/ conserving energy and natural resources/ minimizing environmental impact

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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16. Abstract

This report is a first look at potential ways of generating and distributing electrical power in a modular integrated utilities systems (MIUS) program. Literature surveys were conducted to cover both conventional and exotic generators. Typical ranges of operating conditions and generating efficiencies are described. Those systems that appear to be applicable to MIUS have been indicated, and the criteria for equipment selection are discussed.

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TECHNOLOGY SURVEY OF ELECTRICAL POWER GENERATION AND DISTRIBUTION FOR MIUS APPLICATION

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PREFACE

The Department of Housing and Urban Development (HUD) is conducting the Modular Integrated Utility System (MIUS) Program devoted to development and demonstration of the technical, economic, and institutional advantages of integrating the systems for providing all or several of the utility services for a community. The utility services include electric power, heating and cooling, potable water, liquid-waste treatment, and solid-waste management. The objective of the MIUS concept is to provide the desired utility services consistent with reduced use of critical natural resources, protection of the environment, and minimized cost. The program goal is to foster, by effective development and demonstration, early implementation of the integrated utility system concept by the organization, private or public, selected by a given community to provide its utilities.

Under HUD direction, several agencies are participating in the HUD-MIUS Program, including the Atomic Energy Commission, the Department of Defense, the Environmental Protection Agency, the National Aeronautics and Space Administration, and the National Bureau of Standards (NBS). The National Academy of Engineering is providing an independent assessment of the Program.

This publication is one of a series developed under the HUD-MIUS Program and is intended to further a particular aspect of the program goals.

COORDINATED TECHNICAL REVIEW

Drafts of technical documents are reviewed by the agencies participating in the HUD-MIUS Program. Comments are assembled by the NBS Team, HUD-MIUS Project, into a Coordinated Technical Review. The draft of this publication received such a review and all comments were resolved.

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SUMMARY

This report describes candidate electrical generation power systems for the modular integrated utility systems (MIUS) program. The candidates for the MIUS power generation system are divided into two classes: conventional and experimental. Conventional power systems include the Rankine cycle systems, the Brayton cycle system, binary cycles, reciprocating internal combustion engines, and electric generators. Heat-recovery equipment associated with conventional power systems and supporting equipment are also discussed. Other power systems include electrochemical systems, nuclear energy sources, thermionics, thermoelectricity, solar energy, magnetohydrodynamics, hydroelectric power, tidal power, geothermal power, and wind power. Power distribution is discussed briefly.

The steam and organic Rankine cycle systems, open and closed cycle gas turbines, diesel and natural gas engine/generators, and fuel cells appear to be the most universally applicable power sources for MIUS and will be investigated both singularly and in parallel for use as the prime power source. Energy storage devices including batteries, hydrogen/oxygen generators (water electrolysis), and heat storage devices may be applicable for MIUS plants.

INTRODUCTION

The purpose of this discussion is to describe electrical power generation systems and to indicate candidate systems compatible with the modular integrated utility systems (MIUS) program. These candidate systems will be evaluated in depth during trade-off design studies to select the system best suited to MIUS requirements.

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Systeme International d'Unites (SI). The SI units are written first, and the original units are written parenthetically thereafter.

CONVENTIONAL POWER SYSTEMS

This section describes conventional heat engine systems that are either off-the-shelf items or have reached a state-of-the-art stage in development so that it is reasonable to assume that these systems will approach off-the-shelf status by 1980 to 1985. Current off-the-shelf equipment consists of equipment operating on the following cycles: steam Rankine, open Brayton, and reciprocating internal combustion engines (Diesel and Otto). Binary cycles using combination gas turbines (open Brayton cycle) and Rankine steamplants are also currently available. The cycles in an advanced state of development with a possibility of being available by 1980 to 1985 are as follows: closed Brayton using either air or an organic fluid, Stirling engines, and the Rankine operation using metals such as sodium or mercury potassium alloys as the working fluid.

The principal advantages and disadvantages of these various cycles are discussed briefly so that some preliminary evaluation can be made of their applicability and ease of adaption into an MIUS. Auxiliary equipment with these cycles, such as boilers, generators, and heat-recovery equipment, is also mentioned briefly.

Rankine Cycle Systems

In the Rankine thermodynamic cycle the working fluid is used in the liquid as well as the vapor phase. A simple four-step cycle is shown in figure 1.

During the first step, saturated liquid is pumped to a high pressure. Next, energy is added by heating the fluid in a boiler at constant pressure until it becomes a saturated or superheated vapor, which is allowed to expand through an engine or turbine. During this latter process, useful work is extracted from the engine or turbine in the form of shaft power. In the case of a powerplant, the shaft drives an electrical generator, and the vapor or liquid/vapor mixture then is completely liquified by passing it through a condenser where energy is removed as waste heat. The fluid is then pumped to boiler pressure for recycling.

Reheating is used to increase the thermal efficiency of the Rankine cycle. After the vapor is expanded through several turbine stages, it is removed, reheated, and then returned for further expansion through later turbine stages.

The limitations of structural materials restrict the pressure and temperatures of operation as well as the choice of working fluid. In particular, the use of metals as a working fluid requires complex pumping equipment; and in binary cycles, liquid metal and steam heat exchangers still present formidable detail design problems. The advantages and disadvantages of the working fluids used in the Rankine cycle are listed in table I. The energy (heat) source for a Rankine cycle plant may be fossil fuel, a nuclear reactor, or solar heat.

Water as a working fluid.- Nearly all large central power stations operate on the Rankine cycle using water as the working fluid. The steam in these powerplants is produced by boilers, which can extract over 80 percent of the heat from the fuel. The remaining 20 percent of the heat in the fuel is lost from the stack. The stack temperature must remain above the water condensation temperature to avoid corrosion in the stack. Many auxiliaries such as blowers and fuel supply devices required to support boiler operations require power and further

reduce the amount of deliverable energy. The use of boilers to produce heat allows the use of nonpremium fuels to produce power. However, the deliverable steam to the turbine is subject to further reduction to keep the emissions from the stack at acceptable levels. Sulfur dioxide is a product that must be removed from nonpremium fuels either before firing in the boiler or with a chemical treatment such as the injection of calcium carbonate into the combustion chamber. Various Federal agencies are currently investigating the development of technological means for efficiently removing sulfur dioxide (ref. 1).

The nonpremium fuels also contain considerable noncumbustible materials that produce fly ash. These materials must be removed by electrostatic precipitators, waterspray, bag filters, or other devices. All these effluent control devices require power, thus reducing the output efficiency of the powerplant. Combustion control to reduce the release of oxides of nitrogen and smoke to the atmosphere tends to reduce the available output energy from the boiler. In general, pollution control will probably account for 10 to 15 percent of the input fuel energy to a water Rankine cycle.

The efficiency of the water Rankine cycle is also determined by the turbine throttle pressure and temperature and turbine back pressure. Steamplants have been constructed with throttle pressures of 3.44×10^7 pascals (5000 psi) and operating temperatures of 922 K (1200° F). These plants, however, must be constructed of more expensive materials, which involves a higher capital outlay; and maintenance costs are high. The typical plant installed by utility companies between 1960 and 1970 for producing power in the hundreds of megawatt range have used steam in the 2.41×10^7 pascals (3500 psi) and 824 K (1025° F) range. The typical MIUS installation which might use steam would probably closely resemble the 25- to 100-megawatt units typical of the period from 1930 to 1950, which have operating pressures from 7.58×10^5 to 8.62×10^5 pascals (650 to 1250 psi) and temperatures of 616 to 755 K (650° to 900° F). Apparently not many new developments have been made in boiler units to support systems in the 1- to 10-megawatt range, which might be typical of an MIUS installation and which operate at high pressures and temperatures. Within the realm of MIUS applications, there

is still a need for the development of flash boilers that require much less material and eliminate the potential explosion hazard of the large utility units.

Steam from the boiler is expanded in a turbine to extract mechanical energy. Developmental work in this area has been directed toward larger and larger units. Research failed to disclose any data on smaller units designed or built in the late 1960's to the present date. The smaller low-pressure and low-temperature units (<10 megawatts) will typically have fuel rates of 1.06×10^8 to 1.16×10^8 joules/kWh (10 000 to 11 000 Btu/kWh) chargeable to the turbine compared to large high-pressure and high-temperature units (>100 megawatts) with fuel rates of approximately 7 391 090 joules/kWh (7000 Btu/kWh) chargeable to the turbine. In addition to higher pressure and temperature, the larger units typically use a number of reheat stages to achieve the lower fuel rates. The vapor or vapor/liquid mixture leaving the final stages of the turbine is condensed. The temperature at which condensation occurs strongly influences the efficiency of the overall Rankine cycle. Hence, the method of heat rejection to cool the secondary side of this condenser will influence overall fuel rate. The choice of heat rejection will be site dependent. For a very arid region where water is at a premium, dry cooling towers with a typical temperature of 366 K (200° F) will produce a pressure near atmospheric at the exhaust of the turbine. Where large supplies of cold water are available for cooling, the exhaust pressure of the turbine will be approximately 3.4×10^3 pascals (0.5 psia). Liquid cooling towers will be intermediate and will produce pressures between 3.4×10^5 and 4.8×10^5 pascals (5 to 7 psia).

The steam Rankine cycle has a number of advantages for MIUS applications. Thermal efficiency for smaller plants is good and will approach 30 percent. These plants are easily adaptable to nonpremium fuel, and a wide range of well-known, highly reliable equipment is available. They can operate efficiently over a widely varying load. Steamplants are well established and understood. Finally, heating requirements for site operation can be readily supplied from the steam Rankine cycle.

There are several disadvantages in using steamplants. The use of nonpremium fuels may require extensive pollution control equipment, which adds to the capital cost and decreases the reliability of the equipment. The size of the steamplant must be greater than 2 megawatts if present off-the-shelf equipment is to be used; in general, turbine efficiency of off-the-shelf equipment improves with increasing size, temperature, and pressure. Because this type plant cannot be operated unattended, the labor burden may be higher than with other types of prime movers. There does not appear to be a wide-based research and technology effort to produce cheaper and more efficient boiler and turbine combinations in small sizes that might be used in MIUS. For high-efficiency units, a large volume of cooling water is required, which may cause thermal pollution problems in the supply streams. Finally, this type powerplant requires considerable real estate for fuel supplies, ash-handling facilities, and operating equipment. Tall stacks are used to dilute stack effluents before reaching the ground, which makes an architectural problem in the integration of the MIUS into a residential area.

Organics as working fluids.- A Rankine cycle plant may operate on an organic working fluid such as biphenyl and mixtures of biphenyl and biphenyl oxide, monoisopropyl-biphenyl (MIPB), pyridines, and orthoxylene. The organic Rankine cycle operates in the same general way as previously described. However, the basic difference is that the organic working fluids are type B (have a characteristic temperature-entropy (T-S) diagram with a positive slope saturated-vapor curve); therefore, no superheat is needed because expansion through the turbine produces vapor superheat. This characteristic tends to eliminate turbine erosion found in the two-phase flow of a type A fluid such as water.

A typical T-S diagram for an organic fluid is shown in figure 2. For reference purposes, a T-S diagram is also shown for a type A fluid such as water and the liquid metals mercury and potassium.

The principal advantages of the organic working fluid systems are as follows.

1. Turbine efficiencies are good despite the relatively low turbine inlet temperature (588 to 644 K (600 to 700° F)).

2. Low system-operating pressures 1.38×10^7 to 2.11×10^7 pascals (200 to 300) psia may allow unattended operation.

3. Material compatibility of the system is good.

4. Low flame temperatures can be used in heating, resulting in low oxides of nitrogen (NO_x) emissions.

The organic Rankine cycle has a number of disadvantages. Because of the pyrolytic degradation of the working fluid, operating problems have resulted. The overall thermal efficiency of the cycle is low because of the low throttle inlet temperature, and low turbine back pressure must be maintained to achieve even this low efficiency. This type unit has not achieved off-the-shelf status.

Development of this type cycle has been active during the last few years. Applications of these developments have been evident in the low-power automobile and in military and remote-base uses. The largest system under development is rated at 100 kilowatts electrical. The use of such a unit as the low-temperature half of a binary cycle may be applicable to MIUS.

Liquid metal as a working fluid.- The use of steam as a working fluid in the Rankine cycle severely limits the temperature of the working fluid at the throttle inlet. Temperatures from 699 to 810 K (800° to 1000° F) cause plants to operate at a pressure of 2.41×10^8 pascals (3500 psi). The use of metals as the working fluid can increase the temperature at the throttle inlet and hence the efficiency of the overall cycle while system pressures can be considerably lower. Mercury, which has been used in several plants in the past (ref. 2), can be used at high temperatures with only moderate pressures.

At 810° K, the pressure of mercury is only 1.24×10^7 pascals (180 psia), and mercury condenses at a pressure of 1.35×10^4 pascals (4 inches of mercury) absolute when the temperature is 533 K (500° F). Other metals will show similar high temperatures worthy of consideration. The use of metal as a working fluid is best applied in the topping cycle in conjunction with a steam or an organic liquid bottoming cycle. The temperature range throughout the system from throttle to condenser can only be established by trade-off with the bottoming cycle.

Other metals used, or considered for use, in a Rankine cycle include the alkali metals: potassium, rubidium, cesium, lithium, and sodium. The choice of liquid metal working fluids is affected by such system characteristics as desired heat-rejection temperature, pumping power, and complexity of turbomachinery. Generally, it is desirable to select a liquid metal with low vapor pressure and intermediate density and enthalpy changes across the turbine. The principal disadvantages of liquid metal Rankine cycle systems are as follows.

1. Toxicity of working fluid

2. Materials compatibility problems at high temperature

3. Separation of working fluid from bearing lubricants

4. Corrosion and erosion of turbine blades, pumps, and other system components

5. Potential explosion hazard with sodium and potassium if leak occurs between topping cycle and water bottoming cycle fluid

Boilers.- The steam Rankine cycle power generation system requires boilers to supply the steam. Low-pressure boilers are discussed in reference 3. Boilers used in electrical power generation require high pressures and temperatures and are normally the water-tube type. Factory-packaged units are available in any desired size or range. One total energy site visited produced electricity from steam provided at 386 kilograms (850 pounds) gate at 713 K

(825° F), and drove a 7500 kVA turbine/generator set. Typical boiler efficiency is 80 percent. The General Electric Corporation is working on a small, compact, cool combustion boiler. The lower combustion temperature reduces pollutants NO_x and carbon monoxide (CO). The working fluid (water) is circulated within a porous injector to reduce the temperature. Rocketdyne is building a boiler based on their experience with rocket motors during the Apollo Program. The fuel and oxidizer energy is used to produce steam instead of thrust. The first unit will use liquid oxygen and natural gas and produce 11 megawatts of power. Both these boilers may have possible application to MIUS use.

Brayton Cycle System

Two types of systems will be discussed, the open Brayton and the closed Brayton.

<u>Open cycle gas turbines</u>.- The open cycle gas turbine (fig. 3) consists of a compressor for the compression of combustion and cooling air, a combustion chamber into which the fuel (gas or liquid) is introduced together with the air discharged from the compressor, and the gas turbine. The exhaust pressure for the turbine is the same as the compressor inlet pressure (ambient). For power generation, the turbine shaft drives an alternator, usually through a gearbox for speed reduction. The temperature (699 to 811 K (800° to 1000° F)) of the turbine exhaust gases is high, and the gases may be used for steam production in a heat-recovery boiler. This boiler may be the boost-burner type in which the exhaust gases are used as the oxygen supply for combustion. The cycle may include a regenerative heat exchanger using the exhaust gases to preheat combustion air, thereby increasing cycle efficiency.

The gas turbine has become very popular for both power generation at remote sites such as oil platforms in the ocean and at sites requiring highly reliable power for operation of computers. Several airlines use gas turbines for servicing their computer complexes, and their record has been excellent. These turbines have few moving parts and have operated very reliably, and manufacturers have been extending the time between major overhauls as more operating experience is amassed. These systems are lightweight and

easily transported and set up. A fairly wide range of equipment sizes from 100-kilowatt to the 100-megawatt range is available.

Because of the necessity for operating these machines with premium fuels, natural gas or aircraft jet fuel has been used for most of the operations, which is a disadvantage. Some work has been done on the use of lower-grade fuels. In addition to recognizable problems of turbine blade erosion, these engines have typically low thermal efficiencies of 18 to 27 percent. This low efficiency is primarily due to the temperature limitation of the turbine blading. A typical upper limit for turbine blading material is 1255 K (1800° F), which is economically competitive in today's market. The turbine inlet temperature drops rapidly as the load is reduced, and the low part-load efficiency of these devices is primarily due to this low operating temperature.

Because of the large amount of excess air used to cool the combustion products to the operating temperature of the turbine, the gas turbine exhaust emissions are low. This exhaust from the turbine is capable of supporting combustion; has a temperature from 533 to 766 K (500° to 920° F), depending on the load on the turbine; and can be directed to a boiler that is fired or unfired to produce steam. Combined cycles using the gas turbine and a steam Rankine cycle are commercially available in the 125-megawatt range and above. Fuel rates of less than 9.5×10^7 joules (9000 Btu) (higher heating value) or approximately 36 percent thermal efficiency can be achieved with unfired boilers operating at full load. Approximately 50 percent thermal efficiency has been achieved with fired boilers.

In the past the gas turbine has been a low-pollution device because natural gas fuel and large amounts of excess air have been used. With nonpremium fuels, smoke and sulfur-dioxide emission can be anticipated as problem areas. Noise is also a problem with the gas turbine because of the exhaust and the high flow rates of gas in the inlet ducts. To solve these problems, careful design will be required in MIUS. Some data in this problem area are available in reference 4.

The principal advantages of a gas turbine installation are as follows.

1. These systems are compact, easily transported and set up, and lightweight (approximately 45 to 68 kg/kW (100 to 150 lb/kW)).

2. Lead times for delivery as stated by various manufacturers are short (around 1 year), and the operation of these systems as a topping cycle for a steamplant can be implemented in approximately 2 years.

3. Performance records of small turbines applicable to MIUS are apparently excellent. The Garrett Corporation reports more than 42 000 hours of turbine operation on Western Airlines computer installation without overhaul and between 500 and 1220 days of operation without loss of load on installations of from two to four gas turbines in four installations (ref. 5).

4. The use of natural gas in operating the system results in low emission rates of air pollutants.

The principal disadvantages of a gas turbine installation are as follows.

1. The thermal efficiency of a 50 to 100 percent load is 18 to 24 percent, which is relatively poor.

2. The noise of the exhaust and the inlet ducts may be difficult to suppress.

3. Most operating experience is based on the use of natural gas as the working fluid. The operation of systems on nonpremium fuels has not been extensive.

4. There is insufficient operating data available to estimate the total lifetime of these prime movers.

Closed cycle systems.- The closed Brayton cycle is a thermodynamic cycle that operates completely in the vapor region of the working fluid. In the simple ideal Brayton cycle shown in figure 4, the gas is first compressed isentropically to maximum cycle pressure. Energy is then added to the gas by heating at constant pressure. The hot

gases are then isentropically expanded in a turbine, thus producing useful work. The exhausted gas is cooled at constant pressure and returned to the compressor.

The thermal efficiency is very sensitive to the irreversibilities in the compression and expansion processes, and small losses in these units can have a great effect on overall system thermal efficiency. An increase in efficiency can be obtained by the regenerative process of using a heat exchanger to transfer heat from the exhaust gas leaving the turbine to the gas leaving the compressor. Closed Brayton cycle efficiencies vary with the gases and temperatures used in the cycle but typically are in the range of 15 to 35 percent. The closed Brayton cycle can use virtually any type of high-temperature heat source: solar, nuclear reactor, fossil-fuel combustion, radioisotope, et cetera.

A number of closed cycle gas turbines operating on air systems have been built in Scotland, England, Germany, Japan, and the U.S.S.R., in sizes ranging from 2 to 12 megawatts. These plants were constructed primarily for experimenting with low-grade fuels. The Scottish plant, installed at Altnabreac in 1959, used hand-cut peat (containing 55 percent water) for firing and developed 2000 kilowatts. The Japanese have been testing a closed cycle gas turbine with coal that has ash that is more than 50 percent silicon dioxide. Other plants have been designed to use residual oil with high vanadium and sodium content. These plants typically require a niobium-stabilized, austenitic, stainless-steel heat exchanger to prevent corrosion on the flue gas side or, a minimum requirement for this application is to use some corrosion-resistant ferritic alloy; hence, it is estimated that capital costs of these plants will be considerably higher than equivalent steamplants.

The closed cycle gas turbine offers many advantages over the closed Rankine cycle operating on steam. As has been noted previously, steam temperatures above 872 K are not economical because of the very high pressures (1.38×10^7 pascals (2000 psi)) required; however, the gas turbine can operate at 1072 to 1472 K (1470° to 2190° F) at very moderate pressures. These inlet temperatures can permit plant efficiencies of more than 50 percent. Lower capital

costs and lower maintenance are the potential benefits of the requirement for fewer components.

The closed cycle plant has several advantages over the open cycle. In the closed cycle, the temperatures at the inlet and outlet of the turbine can be kept constant, and the pressure of the working fluid can be used to vary the power output from the turbine. This type operation results in a nearly constant efficiency over a wide load range. The closed cycle can operate on inert monatomic gases such as helium, argon, or neon. Helium has a specific heat that is five times higher than air and a thermal conductivity that is approximately six times higher than air; thus, helium requires only one-fifth the weight of gas passing through a system to perform the same work as air. As a result, small heat exchangers that are approximately one-third the size of those required for air can be used for helium.

An additional advantage of the closed-loop Brayton cycle over the steam Rankine cycle is that the gas circuit requires only approximately one-fifth the cooling water of a corresponding steamplant. A final advantage of the closed Brayton cycle is that the inert working fluid does not corrode or foul the interior of the entire system.

The closed-loop Brayton cycle would appear to be an ideal prime mover for MIUS. Work on this cycle has been pioneered in Europe by Escher Syss Ltd., Zurich, Switzerland; however, there does not appear to be any parallel development in the United States.

Helium will be used in the gas-cooled fast breeder reactor as a cooling fluid with the temperature of operation approximately 811 K (1000° F) and an operating pressure of 1.72×10^6 pascals (250 psi). The conceptual studies indicate efficiencies of 38 percent. A 200- to 400-kilowatt system was developed for the U.S. Army for field power generation but was a very inefficient device. Plants with power levels from 2 to 15 kilowatts and lifetimes of 5 years have been experimentally evaluated at the NASA Lewis Research Center for space power applications. Either a solar or a nuclear source will be used at these plants. A 3-kilowatt closed Brayton cycle was tested and evaluated at the NASA Lyndon B. Johnson Space Center. This plant was operated more than 200 hours.

Binary Cycles

Binary cycles are used when the temperature/pressure range limitations of working fluids in a cycle or the structural/temperature/pressure limits preclude using a single cycle for maximum energy extraction. A second application occurs whenever a gas being exhausted from a cycle has considerable heat content.

For a typical powerplant installation, the flame temperature of any common fuel burned in air will not exceed 2200 K (3500° F). The sink temperature to which heat will be rejected will not be higher than 311 K (100° F). In an ideal cycle, disregarding the heat transfer-throttling process, the working fluid will operate at a temperature not over 2144 K (3400° F). There are no fluids useable in the Rankine cycle that can span this range economically.

The earliest work on combined cycles was performed by Emmett, Shelton, and Hackett of the General Electric Company (ref. 2). In 1923, an experimental mercury turbine with an 1800-kilowatt capacity was installed at Dutch Point, Connecticut. This experiment was sufficiently successful so that by 1928 a commercial installation was made by General Electric for the Hartford Electric Light Company. A 10 000-kilowatt unit followed in 1930, and by 1933 two additional installations followed. In all, six plants were constructed by 1950. Two plants installed in Kearny, New Jersey, for Public Service Electric and Gas Company operated successfully from 1933 through 1950. These plants had a fuel rate of 9 608 417 joules/kWh (9100 Btu/kWh) despite the modest temperatures and pressures in the system (mercury throttle, (8.82×10^5 pascals, 780 K (128 psi, 944° F)); steam throttle, (4.2×10^6 pascals, 714 K (615 psi, 825° F)). At present, there appears to be little interest in mercury-steam binary cycles. The system is complex and capital costs are high. If equipment were available, the inherent problem of mercury spillage close to residential areas would require careful consideration for MIUS use.

During the last 10 years, NASA has sponsored systematic studies of the use of alkali metals as an alternate to mercury for a topping cycle by the General Electric Company, Foster Wheeler, and The Bechtel Corporation (ref. 6). General Electric has proposed to the Office of Coal Research

the employment of this technology in central power stations (ref. 7). Preliminary studies indicate thermal efficiencies from 48 to 60 percent are achievable with this cycle. The studies of Larry D. Simmons (ref. 8) indicate that combinations of lithium and sodium/mercury/water have the potential for thermal efficiencies of approximately 60 percent at temperatures of 2255 K (3600° F). This temperature range approaches the adiabatic flame temperature for common fuels and represents an upper achievable limit on thermal efficiency. Present materials limitations would restrict the operating temperatures to around 1390 K (2500° R), where the thermal efficiency would be approximately 55 percent. Mercury cycles alone cannot reach this level of efficiency because mercury would reach pressures of 2.07×10^7 pascals (3000 psi), which would impose structural limitations.

The binary cycles and the closed Brayton cycle appear to be the most promising of the future developments. Assuming that the lead times for development of lithium or other metals are similar to those for the mercury binary cycle in the 1930's, equipment of this type could conceivably be available for MIUS applications in the early 1980's.

Diamant (ref. 9) shows a cycle in which steam is injected directly into the gas turbine and exhausted out the stack. This type plant requires very-high-purity steam, and a distilling plant is required for makeup. Thermal efficiencies of approximately 43 percent are indicated.

A second topping cycle that is becoming popular is to use an open cycle gas turbine as a topping cycle and generate steam with the hot gases of the turbine exhaust. The exhaust gases from the turbine contain considerable excess air, so that it will sustain combustion. This air is considerably preheated; hence, the steam boiler efficiency is higher than for a conventional boiler.

Reciprocating Internal Combustion Engines

Two types of reciprocating internal combustion (RIC) engines are in common use for power generation. The first type operates on the Otto cycle (spark ignition) using

natural gas or gasoline. The second type operates on the diesel (compression ignition system) using fuel oils of various grades.

In the ideal Otto cycle, fuel and air are taken in during the intake stroke and compressed isentropically. The ratio of the compressed volume to the initial volume is designated as the compression ratio. The compressed fuel and air are ignited with a spark and expand to make the stroke work. The diesel cycle differs from the Otto cycle in that only air is introduced on intake. The air is compressed isentropically to a higher pressure and temperature than in the Otto cycle. Fuel is injected and ignites because of the temperatures, and the work stroke results.

A typical diesel or gas engine used for power generation has a thermal efficiency ranging from 36 to 41 percent. The exhaust gases and the water jackets contain considerable heat that can be recovered. With properly designed heat exchangers, approximately 24 to 36 percent of the input fuel can be recovered by such systems.

There are many parameters that influence the performance of the gas or diesel engine. The gas engine was introduced into common use in the 1960's because natural gas was cheap and plentiful. The gas engine is a modified diesel. Spark plugs are installed to ignite fuel. In gas engines, manufactured gas containing more than 50 percent hydrogen cannot be used. Propane, butane, natural gas, and sewerage gas can be burned in such engines, but timing will have to be adjusted from gas to gas to prevent detonation. In addition to timing, the temperature of the air admitted to the cylinder must be controlled by the compression ratio, the aftercooler temperature, and compression of the gas before admission to the cylinder.

Because many gas engines operate naturally aspirated, cooling of the inlet air is not required. The brake mean effective pressure developed in such engines is approximately 1.17×10^6 pascals (170 psi), and the compression ratio is typically 10:1. The low power output of this engine is a disadvantage. The mean effective pressure can be raised by approximately 20 to 40 percent by using a turbocharger equipped with an aftercooler, but the

engine will require retiming. The mean effective pressure will be raised to approximately 1.38×10^6 to 1.52×10^6 pascals, (200 to 220 psi); thus, for the same cylinder displacement, the power output can be raised as much as 40 percent. The limitation in the increase in power is determined by the water temperature available for cooling the aftercooler.

The diesel engine ignites the fuel by spontaneous combustion. Because the fuel is injected in a solid form, there is some time delay during which the fuel vaporizes before ignition. The fuel, therefore, must be injected early in the compression stroke and can be injected as early as 50° before top dead center. Fuel in a diesel engine should burn as rapidly as possible. Knocking in a diesel engine occurs with slow-burning fuels, and incomplete combustion and smoking can occur with these fuels. To ensure ignition, the compression ratio of the diesel is never below 11:1 and can be as high as 15:1. Compression pressures vary from 3.44×10^6 to 7.41×10^6 pascals (500 to 1075 psi). With turbocharging, the mean effective pressure may be as high as 1.72×10^6 pascals (250 psi), so a diesel engine of the same displacement as a naturally aspirated gas Otto engine will develop approximately 75 percent more power than the gas engine.

The diesel combustion characteristics have been improved by using precombustion chambers. In this case, the fuel injector sprays the fuel into a small chamber connected to the main cylinder. This chamber is small compared to the volume of fuel being injected; therefore, the pressure in this chamber rises more rapidly than in the main cylinder, and combustion occurs. The combustion process vaporizes the remaining fuel and ejects it into the main cylinder in a form that is easily ignited, resulting in more complete combustion. The combined emissions in the exhaust of a diesel thus equipped are reported to be approximately 42 percent of those from a direct-injection diesel (ref. 10).

Fuel costs and dirty emissions are problems with the direct-injection diesel. One method of attempting to correct both these problems is to operate the diesel in a dual fuel mode in which a small amount of pilot oil is injected into the cylinder to start ignition. These engines can develop as much as 1.74×10^6 pascals (252 psi) mean

effective pressure compared to 1.21 x 10^6 pascals (176 psi) mean effective pressure with natural gas as fuel, an increase in power output of 43 percent[1].

The size of the diesel engine influences its efficiency. In general, the higher the rpm, the higher the engine load, the higher the exhaust temperature, and the less efficient the engine; thus, maximum rpm tends to be lower as engine size increases. The decrease in rpm with engine size is shown in figure 5 and tables II and III (ref. 11). Current data concerning any particular engine may be obtained from the manufacturer. As engine speed decreases, the thermal efficiency increases; this is accompanied by some decrease in exhaust temperature. In addition, the heat loss to the water jacket decreases. In the larger engines, pistons are cooled by oil spray, and a larger fraction of the heat is carried off by the lubrication oil. In the smaller engines, to approximately 1500 kilowatts and 720 rpm, the water jackets can be operated to 394 K (250° F). The heat from both the water jacket and the exhaust can be recovered as 1.03 x 10^5-pascal (15-psi) steam for low-pressure steam applications. This mode has been used on Nordberg diesels operating at 514 rpm and developing 1.59 x 10^7 watts (1620 bhp) range. This engine is operated at a mean effective pressure of 1.21 x 10^6 pascals (176.1 psi). If this same engine power output is increased to 1.80 x 10^7 watts (1840 bhp) by supercharging so that its mean effective pressure is raised to 1.38 x 10^6 pascals (200.1 psi), then the jacket temperature is reduced to 358 K (185° F) and only the exhaust heat is available for low-pressure process steam (refs. 10 and 12).

The diesel engine/generator plant system has been used for more than 50 years to provide baseload to small and moderate-sized communities. Throughout Texas, there are numerous small towns with community-owned facilities operating on diesel power. The diesel engine is much more efficient than either the open cycle gas turbine or the small steam turbine at full and partial load. These engines

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[1]Private communications, Mr. Robert Calvert, District Manager, Power Machinery Division, Nordberg Division of Rex Chainbelt, Inc., March 30, 1973.

are capable of quick starts and full loading in a short period of time. When operating in a spinning reserve mode, their fuel consumption approaches 50 percent of that used by a gas turbine. For this reason, there is widespread application of the diesel in hospitals and high-rise buildings for standby and emergency power. In 1970, the diesel supplied approximately 4000 megawatts in general utility service. This amount is expected to reach 8000 megawatts by 1980 and 12 000 megawatts by 1990 (ref. 1).

Units with a 10-kilowatt capacity or less normally have air-cooled, four-cycle, 1800-rpm engines with gear-driven-governors. The alternator usually has a saturated field, four-pole, revolving armature. Output from the generator is either 120 or 240 volts/60-cycle alternating current. The generator is usually directly coupled to the engine crankshaft. Above 10 kilowatts, the engine usually requires water cooling, turbocharging, and hydraulic speed control. The alternators above 10 kilowatts usually have a revolving field and a rotating exciter. Output is in the form of three-phase, 60-cycle, four-wire alternating current. Voltage output is commonly at 480/277 volts. In the larger units of 0.5 to 2 megawatts, the engine speed is normally reduced to 900 rpm or below. The generated voltage can be 4.16 or 13.2 kilovolts. The high costs of controls and switchgear for higher voltages often lead to generation at 480 volts and transformation to 4.16 or 13.2 kilovolts for distribution.

Off-the-shelf heat-recovery equipment for recovery of heat from the exhaust gas is available from many manufacturers. To limit corrosion due to condensation, the existing gas temperature from these heat exchangers is kept above 422 K (300° F). Thus, approximately 67 percent of the heat in the exhaust gas stream can be recovered. The exhaust gases carry off approximately 20 to 25 percent of the total input fuel energy; hence, approximately 14 to 17 percent of this energy can be recovered as 1.03×10^5-pascal processed steam. Another 20 to 25 percent of the input fuel energy is removed by the water jacket and lubrication oil cooler as steam (where ebullient cooling of water jackets is used) and hot water. Approximately 15 percent of the input fuel energy is lost by radiation. Thus, for a diesel engine, between 70 and 75 percent of the input heat energy

can be recovered. Without heat-recovery equipment, only 25 to 41 percent of the input heat energy is recovered.

There are some disadvantages associated with the reciprocating engine generator systems. R. W. Parisian (ref. 13) indicates that the mean time between failures (MTBF) varies from 864 to 287 hours with mean time to repair (MTTR) varying from 2.5 to 5.4 hours for 78 diesels ranging from 2.07×10^7 to 3.63×10^7 watts (2110 to 3700 horsepower). He estimates an availability of approximately 96 percent for continuous-type duty. Of the remaining 4 percent, approximately 1 percent was due to forced outages and 3 percent to scheduled maintenance. In reference 14, Deureaux, chief mechanical engineer, Commission Internationale De L'Eclairage, placed locomotive availability between 92 and 95 percent. In the same paper, G. G. Kibblewhite reported that on British railway locomotives ranging in power from 9.81×10^6 to 3.24×10^7 watts (1000 to 3300 horsepower), availability was between 88 and 90 percent.

Breakdowns on these locomotives occurred in the heating equipment, brakes, and transmissions. These items represented approximately 50 percent of all casualties (breakdowns), which would indicate an engine/control equipment availability of 94 to 95 percent which is in substantial agreement with the information in reference 13. The mean time between casualties (MTBC) reported by Kibblewhite was grouped as bad, average, and good.

Diesel engines accounted for 25 to 35 percent of these casualties. Approximately 25 percent of maintenance time was attributed to casualty repair, which again is essentially in agreement with the information cited in reference 13. Careful attention to maintenance, however, appears to increase the MTBF on British locomotive diesels by about a factor of 4 (brakes, etc., not considered) over those reported in reference 13. These sets of figures are far short of what is required for a complete availability analysis. The percent of rated load is not known, and intermittent operation information is not complete. This reliability data pertains to diesels with a capacity of over 9.81×10^6 watts (1000 horsepower): there is not sufficient data on the variation of MTBF and MTTR with size and rpm to

draw inferences on their variation as these two variables are changed.

The variation of engine maintenance cost, as a function of size, has been extracted from a 1972 report on diesel and gas engine power costs and from data for 1970 and preceding years published by the American Society of Mechanical Engineers (ASME) (ref. 15) and is reproduced in figure 6. The decrease in maintenance cost as engine size increases suggests that the MTBF may be related to maintenance cost or may be longer in larger engines.

The largest diesel engine/generator set observed in a total energy system was rated at 3 megawatts output. Units this size and up to 13 megawatts are available. The normal installation over 1 megawatt appears to consist of a five-unit station where three units supply the baseload, four units meet maximum demand, and one serves as standby.

Reliable off-the-shelf control systems are available to provide automatic paralleling, startup, time correction, shutdown, load shedding, load sensing, alternating, et cetera, for units 100 kilowatts or larger. The less expensive governors on the smaller units do not allow reliable automatic paralleling.

In the 1963-1964 time period, the natural gas industry began promoting total energy gas engine plants. The engine/generator manufacturers cooperated by redesigning almost all their diesels to operate on natural gas. Today the most economical total energy sites use two fuels. The engines operate on natural gas (interruptible rates 8 to 9 months of the year) and diesel fuel during the winter months when there is a greater demand for gas heating.

Diesel fuel operation offers the following advantages.

1. Reliability

2. Low cost and high Btu content

3. Greater efficiency and savings in fuel costs as the size of unit increases

4. Reduced service and repair needs with the absence of points, plugs, and condensers

5. Underground storage unnecessary for safety because the high flashpoint and low volatility of diesel fuel reduce the possibility of fire or explosion from fumes and leakage

6. Prompt engine starting, operating speeds reached quickly, and easy handling of lugging loads

Natural gas operation offers the following advantages.

1. Combustion more complete than with diesel fuel because natural gas mixes readily with air

2. In the past, lower cost per Btu with natural gas than with diesel fuel

3. Low emissions, hence, less need for pollution control equipment

4. No storage tanks

Electric Generators

Generators for supplying the MIUS electrical requirements are available in a wide range of sizes, speeds, types, and control methods. Many engine manufacturers offer package arrangements in which the generator and prime mover come as a unit on the same skid. Although generators are available that generate either alternating-current or direct-current power, alternating-current power generators are of prime interest for MIUS application because most domestic and commercial loads use alternating-current power. The following criteria will influence the selection of generators for MIUS use.

1. Efficiency in converting mechanical energy into electrical output at various loads

2. Electrical load profile, including frequency and power factor requirements

3. Phase balance capabilities

4. Equipment costs

5. Motor starting current requirements

The output frequency of alternating-current generators is a function of rotative speed and number of poles. For example, to provide 60-cycle output, the speed may range from 3600 rpm for a two-pole machine to 900 rpm for an eight-pole machine. A variety of means exist to match generator speed to prime mover speed without reducing the efficiency of either unit. Where gross incompatibilities of generator speed and prime mover speed exist, a gearbox is used to couple the two components.

Generator efficiency is a nonlinear function of the load and is usually maximum at or near the rated load. The range is 90 to 96 percent from a quarter to a full load. In general, the larger the power output from a generator, the higher its efficiency. The Waukesha Motor Company (ref. 16) indicates that for 1200-rpm generator sets, generator efficiencies at full-load continuous capacity and 0.8 power factor vary from 96.2 percent between 1056 and 1300 kilowatts to 93.5 percent at 225 kilowatts, while 1800-rpm-set efficiencies vary from 94.3 percent at 400 kilowatts to 92.0 at 150 kilowatts.

The variation of generator efficiency with voltage and load for larger diesels where a range of generating voltages are available is shown in table IV (ref. 12). Most generators are designed to handle an overload of 20 to 25 percent for several hours. If steady-state overloads are possible, a generator ventilation system will be needed to cool the windings. The ability of the prime mover to accommodate the overload must also be considered. Although a function of the load, proper phase balance is extremely important. Assuming that power factor requirements have been met, driving three-phase motors from the three-phase generator presents the best phase balance. Driving single-phase motors and building lighting may cause improper distribution of the single-phase loads, leading to harmonic distortion, overheating, and electrical unbalance of the generator. Phase imbalance can be held to within 5 to 10 percent by proper distribution of system loading.

Voltage regulation is provided by using static converters or rotating direct-current generators to excite the alternators. Voltage regulation should be within 2 percent from full load to no load. Accurate voltage sensing is necessary to control the response to load changes and the excitation of paralleled alternators to assure proper reactive load division.

Total system power factor is reflected to the generator and should be at least 0.8 if the generator is to be used efficiently. The MIUS program will use off-the-shelf generators. Trade-off studies will concern optimum size, speed, efficiency, cost, and compatibility with the prime mover.

Heat-Recovery Equipment

The purpose of heat-recovery equipment is to salvage otherwise wasted heat energy for other functions. In total energy applications, the primary source of this waste heat is from the combustion process used for electrical power generation. In an MIUS system, waste heat may be recovered from other sources such as waste-treatment processes, but this discussion will be limited to power generation heat-recovery methods only.

On-site generation provides an opportunity for using the fuel energy not converted by the prime mover into shaft horsepower. If the waste heat is not used, the plant efficiency is only that of the prime mover. Overall powerplant efficiency can often be significantly increased with heat-recovery equipment. Heat is recovered from the reciprocating internal combustion engine prime mover from three sources: the lubricating system, the coolant jacket, and the exhaust. The portion of energy recovered from each source is a function of the application, type of prime mover, operating temperature, and efficiency of the recovery equipment.

Most engine designs use the lubricating system to remove some heat from the engine. If there is a demand, this heat can be recovered by an oil/water heat exchanger. The heat is then transmitted by the water loop to meet various heat requirements. If there is no attempt at heat

recovery, the lubricating oil may be distributed to a radiator for cooling. Between 3 and 5 percent of the total fuel input can be recovered from the lubricating oil. Generally, the operating temperature of the engine is significant in determining the proportion of heat removed by the lubricating oil. This may warrant operation of the oil coolant at a temperature high enough to permit direct use in a process such as domestic water heating.

In the case of reciprocating internal combustion engines, cooling jacket heat recovery includes water cooling circuits in the block and heads. Engine jacket cooling removes approximately 15 percent of the fuel heat input to the engine. Depending on the engine type and application, operational temperatures cover a wide range, but, to avoid thermal stresses, the temperature rise through the jacket should not exceed 263 K (15° F). Heat recovery from engine jackets is performed by circulating water from the engine to the heat exchanger. The cooling system can be designed to recover the engine heat in the form of high-temperature water (358 to 405 K (185° to 270° F)) or low-pressure steam 1.03×10^5 pascals (15 psi) as in the ebullient system. This recovered heat energy is used for process loads including hot water heating systems for comfort and process, absorption chillers, and domestic hot water heating.

Certain limitations must be placed on recovery of heat from water jackets. Flow rates of coolant must be held within design specifications to avoid thermal shock and erosion. Often heat storage tanks are required to smooth out temperature fluctuations as engine power demands change.

Flashing the heated liquid into steam and using steam as the distribution fluid is another method of protecting the recovery system. By using back-pressure regulators, the water pressure on the jacket can be kept uniform throughout engine temperature fluctuations. The use of steam requires some modifications in the distribution system, but this method of cooling is suitable for operation to 6.8 kilograms (15 pounds), 397 K (255° F) using standard ASME code components.

Many types of exhaust gas heat-recovery equipment are available. Because engine exhaust must be muffled to reduce noise levels, most recovery units also act as silencers.

Types of equipment that perform this dual function include coil-type water heaters with integral silencers and water-tube boilers with steam separators for gas-turbine and engine exhaust. In each case, the energy is transported to a heat exchanger for conversion into process heat requirements. As in many applications of heat-recovery equipment, the demand for heat varies widely.

Because of the practical limitations of heat-transfer equipment, not more than 70 percent of the exhaust gas heat is salvaged. Approximately 20 percent of the total fuel heat input to an internal combustion engine can be recovered from the exhaust, while an additional 20 percent, approximately, can be recovered by using ebullient-cooled water jackets. In the case of the gas turbine, approximately 50 percent of the input heat can be recovered from the exhaust. The heat-recovery equipment must not have an adverse effect on the primary function of the prime mover to produce work. This necessitates maintaining back pressures within a desirable performance range. A minimum stack temperature of approximately 435 K (325° F) is necessary to prevent condensation of exhaust vapors and corrosion. Other than these limitations, exhaust gas heat recovery is an attractive energy source and contributes to the complete heat-recovery system to increase overall cycle thermal efficiency well above the basic level.

Because heat recovery uses water and steam extensively for carrying away heat energy, some water treatment must be performed to maintain acceptable efficiency and operational lifetime. Scaling, corrosion, and deposit buildup can be managed to tolerable levels with the use of modern multipurpose liquid chemicals. Water treatment and management are discussed in reference 17.

It is apparent that any energy conservation utility system such as MIUS must make full use of all practical heat-recovery equipment. The primary questions center around how much and what quality waste heat is available. Heat recovery from reciprocating and turbine prime movers discussed herein is mandatory to raise operating efficiencies to acceptable levels for MIUS. The practicality of recovery from other energy sources such as waste treatment and incineration may add to the conservation efficiency.

Auxiliary Equipment

There are many items of auxiliary equipment required by MIUS that have not been discussed. Some of these items are pumps, motor starters, valving, transducers, monitors, fuel tanks, inverters, filters, lightning protection, et cetera. These items will be evaluated after the MIUS power generation system has been defined. This evaluation applies to the conventional systems as well as to those in the following section.

OTHER POTENTIAL POWER SYSTEM CANDIDATES

This section describes the nonconventional power systems that are not available as off-the-shelf items and that require various levels of research and development for MIUS use. The advantages and disadvantages are discussed together with the NASA experience with these systems. Electrochemical systems, nuclear energy, thermionics, thermoelectricity, solar power, and magnetohydrodynamics are discussed with brief descriptions of natural power sources such as hydroelectricity, tidal, geothermal, and wind power.

Electrochemical Systems

Fuel cells.- A fuel cell (fig. 7) is a device that converts chemical energy directly into electricity, thus bypassing the thermal conversion process and avoiding the limitation of the Carnot efficiency. The fuel cell is often described as a primary battery in which the fuel and oxidizer are stored external to the battery and are fed to it as needed. Within the battery, the fuel and oxidizer are combined isothermally, converting the chemical energy released directly to electrical energy.

The required system voltage is achieved by connecting cells in series while parallel hookups produce higher power levels. Fuel cells being developed for commercial applications use hydrogen (produced from natural gas or other source) as fuel and air as the oxidizer. The unit that produces the free hydrogen by combining fossil fuel and

steam through a catalytic reaction at elevated temperatures is known as a reformer.

The fuel cell produces direct-current power; therefore, for conventional alternating-current power distribution, an inverter is required to operate with the fuel cell. Solid-state technology has made it possible to achieve conversion efficiencies exceeding 90 percent for these devices with high reliabilities. The typical operating efficiency of a fossil-fuel reformer, fuel-cell inverter system is approximately 30 percent[2].

A possible additional advantage of the fuel cell is that it can be operated in conjunction with an electrolysis cell to produce hydrogen and oxygen during off-peak electrical-load periods. The hydrogen can be stored for use later during peak loads, and the oxygen can be used in other processes.

Fuel cells have been developed that operate on hydrogen as the fuel and oxygen as the oxidizer. The direct use of hydrazine as fuel and hydrogen peroxide or air as oxidizers are the only other alternatives. For operation on less exotic fuels, a reformer that will generate hydrogen from other fuels is an integral part of any fuel cell system. The generation of hydrogen from other fuels affects the design of the fuel cell. One electrolyte used in the hydrogen-oxygen system is a solution of potassium hydroxide. This solution will become contaminated with carbonates if a reformer gas is used. The electrodes used with the potassium hydroxide solution can be nickel, but with reformer gas these electrodes become poisoned. Sulfuric or phosphoric acid can be substituted for potassium hydroxide, but now the electrodes must be changed to platinum or silver palladium. This fuel cell is not economical because of the electrode or catalysis cost of these rare and expensive materials. To reduce electrode cost, an alternate-type electrode is constructed. These electrodes are composed of a support matrix of Teflon or other polymer in which a finely dispersed catalyst of platinum, silver palladium, or

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[2]Private communications, J. Schmitt, Pratt & Whitney, December 1972.

carbon (commonly in graphitic form) is imbedded. Recently, fuel cell operations on a hydrogen air cycle have been reported with platinum catalyst loadings as low as 0.25 mg/cm^2 (ref. 18). Recent work with tungsten carbide may reduce electrode costs (ref. 19). The operating temperature of the alkaline electrolyte system is usually below 472 K (390° F). The temperature of operation of the acid electrolyte is determined by the strength characteristics of the electrodes, when a matrix is used. Conservative practice usually dictates temperatures of 338 K (150° F) or below.

To be useful in an MIUS environment, the fuel cell should have the capability of operating with fuels other than hydrogen. In the petrochemical industry, methyl alcohol and ammonia are commonly available in other applications. The use of natural gas, gasoline, various fuel oils, coal, and producer gases are all potential fuels for the fuel cell. Methyl alcohol and hydrazine have been used directly in an acid electrolyte fuel cell with silver palladium anodes. For an MIUS application, the commonly available fuels are more suitable, but changing these materials to suitable fuel cell applications may require several steps. The first step, using coal or very heavy oils, is to make a producer gas or to crack the heavy oils into a gas to produce gas. The oxides of carbon should then be eliminated by a reformer. For fuels containing considerable impurities, some purification systems may be required. Carbon monoxide tends to reduce the output voltage, and other trace materials can poison electrodes.

Alternatives to the low-temperature aqueous-electrolyte fuel cells are cells operating with molten carbonate or solid oxides. The molten carbonates operate at temperatures between 772 and 972 K (930° and 1290° F) while the solid oxides operate between 1172 and 1372 K (1650° and 2010° F). These systems operate with inexpensive electrodes. For fuels rich in hydrogen, both systems may be capable of combining the reformer system with the fuel cell. Some type of prereactor may be required to condition low-grade fuels. However, to eliminate sulfur and other impurities, it should also be noted that there is high-grade recoverable heat from both these processes.

Theoretically, fuel cells are not limited to Carnot cycle limits of efficiency, and theoretically their thermal efficiencies can exceed 95 percent. A typical hydrogen-oxygen fuel cell can produce 0.9 volt at approximately 60-percent efficiency with a moderate current density (100 to 200 ma/cm²). The decrease in efficiency from the theoretical is due to irreversibilities occurring at the electrodes and the internal resistance of the cell. When a reformer is introduced into the system and heating occurs in the electrolyte, further reductions in the output efficiency occur. The Pratt & Whitney alkaline fuel cell that operates with natural gas and a reformer is estimated at approximately 30-percent efficiency from 60 to 100 percent rated capacity[3]. Air cooling is currently used with a nominal exhaust temperature of 322 K (120° F); hence, a similar cycle operating on ammonia has been reported in reference 20. Both the molten carbonate and the solid oxides are reported to show design efficiencies in excess of 30 percent. Whether these cells would have the added advantage of heat recovery is not known. The solid oxide operating temperature is high enough to consider its use as a topping cycle. The development program conducted by Westinghouse for the Office of Coal Research (ref. 21) which ended in 1970 concluded that practical oxide cells could be developed, but this approach is not presently being pursued. Some engineering analysis of the performance of molten carbonate systems is contained in reference 22; some concept of the solid-oxide fuel cell status in Europe is contained in reference 23.

The principal advantages of fuel cells are as follows.

1. Relatively high electrical conversion efficiency

2. Low (or negligible) air and water pollution. There may be problems with associated gas generation equipment.

3. Quiet operation

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[3]Private communications, J. Schmitt, Pratt & Whitney, December 1972.

4. Modular construction

5. Potential multifuel capability

6. Possible operation with electrolysis cell for peak shaving

The principal disadvantages of fuel cells are as follows.

1. High unit costs for fuel cell and inverters

2. Possible requirement for scarce, precious metals (platinum, for example) as a catalyst on the cell electrodes

3. Short-lived fuel plates in aqueous cells

<u>Batteries</u>.- Batteries are electrochemical devices that operate on the principle of mutual oxidation-reduction reaction for the production of electricity. They are not considered practical as primary power sources because some means of recharge is required. However, storage batteries are useful as emergency (short term) and peak-shaving devices. In these applications, storage batteries or rechargeable batteries could be used. After the electrical energy has been depleted from a storage battery, the process may be reversed by passing current through the cells in the opposite direction and thereby restoring the battery to its maximum energy state. Peak-shaving batteries are being developed in the 10 milliwatt-hour size range and are expected to be available for on-line use electrical powerplants by 1980. The most promising type for this application is the sodium-sulfur battery currently being developed by Electric Storage Battery Technology, Atomic International, and others.

Although any two dissimilar metals in a conducting electrolyte will produce a voltage, relatively few combinations are of any commercial value. The lead-acid, nickel-iron-potassium hydroxide, and nickel-cadmium-potassium hydroxide batteries compose virtually all those available in the commercial market. The types listed above have been used in applications ranging from automobiles to spaceships. The attributes of the storage battery are (1) reliability, (2) useability in remote locations, and (3)

capability for delivering large quantities of power for short periods of time, then being recharged at low rates over extended periods of time.

In choosing a particular battery system, the nominal life, recharge efficiency (may be as high as 90 percent), high current-voltage discharge characteristics, required maintenance, and operating temperatures must be examined. Much research is being conducted on battery-associated technologies; however, state-of-the-art units are satisfactory for those MIUS situations dictating their use. The initial cost of battery systems is the limiting factor in the acceptability of their use as load-leveling devices for a major portion of the peakload.

Nuclear Energy Sources

Nuclear energy sources include nuclear fission reactors, radioisotopes, and nuclear fusion reactors. The common feature of these energy sources is that they all produce thermal energy that can be used for power generation.

Nuclear reactors of the boiling water and pressurized water types are in the production stage and are being constructed at an increasing rate. These are thermal reactors that require neutron-moderating materials to "slow down" neutrons to thermal energy levels for sustained and stable operation. Other thermal reactors include high-temperature gas-cooled reactors and liquid-metal-cooled reactors. More advanced reactor systems that are now under intensive development include gas-cooled and liquid-metal-cooled fast-breeder reactors.

Certain radioisotopes are used as thermal energy sources in numerous applications where the thermal requirement is low (several hundred thermal watts). The systems for nuclear auxiliary power (SNAP)-27 radioisotope thermoelectric generator (RTG) that powers the Apollo lunar surface experiments package (ALSEP) uses approximately 1500 watts (thermal) of refined plutonium-238 as the energy source. Other SNAP systems have also used plutonium. Several Navy navigational buoys use RTG's for power with radioactive strontium as the heat source. Nuclear fusion

systems are still in an early research phase, and even though they continue to receive considerable development funding, no fusion power generation system is expected to be available before 1990.

With respect to MIUS application, the only potentially feasible nuclear energy systems are compact nuclear reactors (5 to 20 megawatts thermal) and possibly fission product radioisotopes taken from large commercial nuclear reactors as radioactive wastes. For economic reasons, nuclear reactors are normally built as large as practical (3000 to 5000 megawatts thermal); however, the possible use of waste heat is not considered in these cases. By using residual powerplant heat, the size/cost trade-off may tend toward economic feasibility of small, compact reactors, but it should be recognized that there is no major research thrust to provide this technology in the near future.

With the proliferation of large reactor plants in the future, a large quantity of waste fission products will be generated. These products generate heat at a low rate and must be safely disposed. It may be practical to consider processing and encapsulating sufficient quantities of these radioisotopes to produce heat sources for power generation and/or heating. The principal problems to investigate are refining processes, costs, and radiological safety considerations.

Thermionics

A thermionic energy converter (fig. 8) is a heat engine that uses electrons as the working fluid. Electrons escape from the hot electrode (emitter) by virtue of their kinetic energy and flow to the interelectrode region to the collector. Useful work can be obtained from this heat engine if the electrons that have arrived at the collector have sufficient kinetic energy to overcome the electrodes potential barrier. This is partly determined by the work functions of the two surfaces. Cesium vapor is introduced in the interelectrode region to reduce the electron space charge and to control the effective work functions of the electrodes.

Typical conditions for operating a thermionic diode are an emitter temperature of 2000 K; a collector temperature of 1000 K; electrode spacing of 2.54×10^{-4} meters (10 mils); a cesium pressure of 267 pascals (2 torr); 15 percent efficiency; an output voltage per cell of 0.7 volts; and an electrical power density of 5 W/cm^2.

The principal advantages of thermionic conversion are as follows.

1. Static conversion, no moving components

2. High-temperature heat rejection (waste heat can be effectively radiated to space or used in a bottoming cycle for additional power generation)

3. Potentially long life

The principal disadvantages are as follows.

1. High cost of thermionic diodes

2. Very-high-temperature 2199 to 2477 K (3500° to 4000° F) source required to achieve good efficiency

Thermionic power generation systems using a nuclear reactor heat source are currently under development for advanced spacecraft applications but are not expected to be operational before 1980. Therefore, thermionics is not considered a viable candidate for MIUS use.

Thermoelectricity

The principal components of a thermoelectric generator are the "P" and "N" materials (fig. 9). Certain semiconducting materials develop a relatively large voltage when a temperature gradient is imposed across them. For an N-type semiconductor, the thermal energy on the hot side excites more electrons into the conduction band than are excited on the cold side, and these excess electrons diffuse toward the cold side. Thus, for an N-type material, electron flow is from the hot side to the cold side. For a P-type material, the thermal energy at the hot side excites an excess of electrons from the valance band into an

intermediate energy state, thus leaving an excess of holes on the hot side. Electrons migrating from the cold side to fill the excess holes produce an electron flow in a P material from the cold side to the hot side. P-N couples are used in a thermoelectric device, and the P and N materials are connected electrically in a series and thermally in parallel. An important parameter for thermoelectric materials is to have a large Seebeck coefficient (amount of voltage rise per unit temperature difference) in the temperature range of interest. Typical operating conditions for a lead tellurium couple are a hot temperature of 866 K (1100° F); a cold temperature of 477 K (400° F); a voltage of 200 millivolts; and an efficiency of 6 percent.

The principal advantages of thermoelectricity are as follows.

1. Static conversion process, no moving parts

2. Variable heat source capability (fossil fuel, nuclear energy, or solar power)

3. Potentially long life, low maintenance

The principal disadvantages of thermoelectricity are as follows.

1. Very low thermal efficiency

2. High cost

3. Very large capacity, high-energy density, thermoelectric converters require use of liquid-metal heat-transfer circuits

Thermoelectric generators using a radioisotope as the heat source have been developed for a variety of low power level applications (10 to 100 watts) including the ALSEP SNAP-27 power supply and general RTG power source for many navigational buoys.

Solar Energy

There are two processes for converting solar radiation into useable energy. One is related to heat collection and concentration, and the other is based on solar energy excitation (photovoltaic conversion).

Thermal processes are in existence for obtaining heat at various temperatures. The range of temperature depends on the degree of concentration and the collectors used. In terrestrial applications, for temperatures under 373 K (100° C), flat black plates are used to heat water. Above 373 K (100° C), a lens to focus the sunlight is required. Photovoltaic devices (solar cells) convert sunlight energy directly into electric current.

The most widely used solar cells are constructed of silicon and produce small voltages at milliwatt power levels. A silicon solar cell designed for spacecraft application typically has a conversion efficiency of 12 to 14 percent. An Earth-bound power source would have a large array of cells wired in parallel and series to obtain useful voltages and current levels.

The NASA has extensive experience in solar power systems. Some specific developments are as follows.

1. Mariner spacecraft - 7.7 square meters (83 square feet), silicon cells, 850 watts

2. Nimbus weather satellite - 4.7 square meters (50 square feet), silicon cells, 450 watts

3. Skylab - manned Earth-orbital spacecraft: 223 square meters (2400 square feet), 24 kilowatts.

4. Space station solar array technology program: 929 square meters (10 000 square feet), 100 kilowatt.

Substantial reduction in cost and size is necessary before a solar cell system can be used for an MIUS. The heat-collection systems are of little value because of the large areas required for assimilation. There is a storage problem with both systems because of the continuing need to

deliver energy at night and during adverse weather conditions.

In general, the thermal-collection systems in use at present are suitable for collecting high entropy heat, but to date no mechanical energy conversion or refrigeration machinery has been built in housing applications. Heating experience is discussed in reference 3.

Magnetohydrodynamics

The magnetohydrodynamics (MHD) generator (fig. 10) is similar to a conventional turbogenerator except that in the MHD device, the working fluid, which is highly ionized gas or plasma, is the electrical conductor. The plasma is forced through a magnetic fluid to generate power. This power replaces the turbogenerator in which working fluid causes a turbine wheel to move and thereby forces a conducting wire through a magnetic field. The MHD generator consists of a duct through which the plasma flows and large magnets on the outside of the duct to produce the magnetic field. Electrodes are located at the top and bottom of the duct to collect the electrons and ionized molecules. Because the conductivity of most gases is quite low at even several thousand degrees Kelvin, low ionization potential additives, such as the alkali metals, are introduced to "seed" the plasma. With the addition of 1 percent of seeding material, acceptable conductivities can be obtained at gas temperature of approximately 2000 K (3200° F). An alternative to using seeded gases is to use a high-conductivity liquid metal.

Although the feasibility of the MHD plant has been demonstrated, many problems remain to be solved in this early stage of development before this type plant will be a conventional power supply. This source of energy is being developed in large power supplies (approximately 25 megawatts) in Russia, but it is not considered a likely candidate for MIUS applications. Summary articles can be found in references 24 and 25.

Hydroelectric Power

A hydroelectric powerplant converts the potential energy of stored water into electrical energy through a hydraulic turbine-driven generator. Pumps are sometimes installed so that excess transmission line power during low-demand periods can be used to store water or equivalent power. This power can then be used during peak periods. Because of the limited regional application of hydroelectric power, it is not a candidate for the MIUS power system.

Tidal Power

Electrical energy can be obtained from the mechanical energy of tides by using the hydroelectric powerplant as described in the previous section. However, the method of obtaining the hydraulic potential energy is different. The hydroelectric plant uses a dam on a river while a tidal power uses a basin that is filled during high tide and closed when the tide recedes. The trapped water is then allowed to flow back to low tide level through a turbine that drives a generator. To provide more flexibility, the suggestion has been made that two or more basins be used so that one basin generates during filling and another during the emptying stage. However, because of the localized applicability of the system, tidal power is not considered applicable to MIUS.

Geothermal Power

Geothermal energy in the form of steam from natural underground sources is being used to a limited extent (400 of the 700-megawatt present world capacity is in Italy) for power generation. If the steam has sufficient volume, temperature, and pressure, it may be piped to the surface and expanded through a turbine. The turbine drives a generator to produce electrical power. As with hydroelectric and tidal power, geothermal power is not considered applicable to MIUS because of the limited regional availability.

Wind Power

Windmills have been used as a source of power for hundreds of years. Energy is obtained from the wind by momentum exchange with a propeller. The American multiblade type, as used for pumping water on American farms, uses approximately 30 percent of the kinetic energy of the wind. The Dutch four-arm type uses approximately 16 percent. The high-speed propeller type uses approximately 42 percent. Windmills have no fuel costs and minimum maintenance. With the availability of alternators with field control, useful power levels can be obtained at lower windspeeds. The efficiency of the of the windmill/generator system is typically approximately 37 percent. The maximum theoretical efficiency is approximately 69 percent. The power output of a windmill is proportional to the cube of windspeed and the square of propeller diameter. The disadvantages of the wind generators are low reliability because of daily and seasonal windspeed variations and the requirement for an energy storage system. Wind-driven generators might be used for an MIUS complementary power source in low population density sites where fuel supply is limited.

Other Heat-Engine Systems

Other heat-engine-type systems that are potentially applicable to MIUS include the Ericsson, Stirling, and Feher cycles. Although prototype, developmental, or experimental models of these cycles have been built and operated for limited periods of time, they are still in the early development stage. No production models of these engines are available.

ELECTRICAL POWER DISTRIBUTION

Electrical power distribution systems include transformers, conductors, switchgears, control systems, and protective devices used in the transmission of electrical energy from its source to the load. Automatic paralleling of multiple generators, power factor correction, passive energy storage, and emergency systems are also included in this group.

Although there have been many refinements in the more passive elements, basic operational theory in components such as transformers, capacitors, relays, et cetera, has remained unchanged. The engineering task involved in these areas is one of selecting the optimum system configuration to match operational requirements. Advancements in electronics have precipitated more control automation, thus reducing the number of required operators and increasing overall efficiency.

The purpose of this section is to assess the technology in the field of power distribution to gain insight into possible configurations for MIUS. Typical of residential and light industrial loads is the widespread use of single-phase, 60-cycle alternating current at 110 and 220 volts. Within the range of MIUS concepts, it is generally not economical to generate power at such low voltage levels because of voltage drop in the distribution system and conductor size. Thus, it is necessary to transform voltage and current from one level to another to optimize generation and utilization criteria.

Transformers

Transformers are generally classified by power rating and type of cooling. These factors are interrelated because the rating of a transformer is determined by the amount of heating due to hysteresis and eddy currents in iron cores and the resistance of windings. As units become larger, various types of heat-dissipating techniques are used to maintain internal temperatures low enough to prevent insulation breakdown. Self-air-cooled units can be obtained with capacities of 3000 kilovolt-amperes at 15 000 volts. Forced-air-cooled units may be obtained in ratings to 15 megavolt-amperes with voltages to 35 000. Other units use fluids such as water and oil for cooling, depending on size, location, and use.

Several standard connections are possible with three-phase service. These consist of the delta, open-delta, or wye connections. A characteristic of the delta connection is that three-phase service is not lost with the breakdown of one transformer. If one transformer is out, the other two operating open delta will provide reduced three-phase

power. Open-delta installations are frequently made where considerable future increase in load is expected. The increase can be accommodated by adding the third transformer to the bank at a later date. The wye connection has the advantages of a groundable neutral, two single-phase voltage levels, and a three-phase load capability. Normally, the wye connection would be considered the prime MIUS candidate. With three-phase installation, a trade-off must be made as to the suitability of one three-phase transformer or three single-phase transformers. Advantages of a single three-phase transformer over three single-phase transformers can be summarized as follows.

1. Lower cost

2. Higher efficiency

3. Less floor space and weight

4. Simplification in outside wiring

5. Reduced transportation and installation expenses

The disadvantages of the single three-phase transformer are as follows.

1. Greater cost of spare units

2. Greater derangement of service in the event of a breakdown

3. Greater cost of repair

4. Reduced capacity in the self-cooled units

Although the primary-system units represent most of the transformer costs and design, smaller units are found dispersed throughout most systems. These units are used for isolation, voltage boosting, motor starting, control, monitoring, et cetera, and present many areas where considerable engineering effort must be expended in the design of a complete system.

Some viable state-of-the-art techniques, such as supercooling of units to reduce losses and size, have

recently been demonstrated; however, none of these are considered to be applicable to present MIUS usage.

One of the trade-offs involved in selecting a transformer size is the distribution voltage level. In general, the smaller the installation, the lower the distribution voltage. Distance between loads, transformer and cabling cost, and switchgear must be considered in the selection of a voltage. Tendencies are to use as low a voltage as practical in the generator; to use lower voltage switchgear; and, for long distance or high power, to boost the voltage for transmission.

Conductors

Environmental, esthetic, and safety factors combined with advanced technology have greatly influenced the design of conductors used in electrical power distribution systems. Improvement in the metals has produced more flexible conductors with better corrosion resistance, and electrical insulation that has good dielectric aging characteristics and can withstand prolonged temperature extremes and high humidity has increased system reliability. Thermoplastic insulation, for example, has the desirable characteristics of toughness and long life, is nonoxidizing, and is comparable to rubber in dielectric strength. These qualities make it possible to reduce the thickness of the insulation used as compared with rubber compounds and to omit protective covering over the insulation.

The selection of a particular conductor type for a given application may be based on many diverse factors including current, voltage, length of run, heat rise, load factor, type installation, and applicable safety codes. The MIUS will use standard off-the-shelf electrical conductors as specified by the National Electrical Code.

Switchgear

The large class of electrical equipment generally referred to as switchgear may be divided into two voltage-dependent categories. High-voltage switchgear provides for the required control and metering equipment for generators,

transformer supply circuits, feeders, large motors, et cetera, for systems with a maximum of 15 000 volts. Low-voltage switchgear includes basically the same function for system voltages under 600 volts. A large variety of standardized units exist that are readily available to perform all required MIUS functions. In either range, units are available with circuit breakers, fusible switches, or a combination of these. A variety of enclosures are available for both safety and weatherproofing under various ambient conditions.

Because switching functions must often be performed during or after a power failure, much of the switchgear is battery powered. These batteries are maintained in a charged condition and can be used for control circuitry, motor starting, and emergency systems as well as for switching. For small installations, there are some instances in which these batteries might even be used for load leveling. Much of the feasibility of using batteries for peakload periods depends on identification of areas where direct current may economically displace alternating current and on the availability of high-energy density low-cost cells.

Modern electronic control circuits have made the differentiation between switchgear and controls a little more pronounced; however, some areas exist where one piece of hardware may be used for control and switching. In general, the control circuit is low-power hardware that manipulates the switchgear, thus controlling larger loads.

Loading

In all electrical subsystems, equipment rating is determined largely by loading conditions. Properly designed power generating and distribution systems are capable of withstanding high surge and overload conditions (dependent on time and duration). The overriding consideration in selecting particular systems is the peakload.

For a given population sector, the load profile varies as a function of the requirements of that group. In a large network, the effects of individual household appliance usage are small. As system size is reduced, fluctuating power

requirements present more of a problem. The speed control and variable load-handling capability of a small generator are critical because percentage load variation is much more pronounced. A very short response time with minimum overshoot is mandatory or individual load actuation will cause marked voltage variation. The power distribution system must also be chosen to minimize voltage variation effects. If, for example, a single service is used, the dwelling on the end of the line might have a very large variation in voltage due to line losses. Proper voltage regulation at the generator and an efficient distribution system will provide the household with an acceptable power source. Attention must next be focused on decreasing peakload requirements. The MIUS concept can alleviate some loading problems by allowing some internal loads to be activated during non-peak-periods. In this manner, the generator may be operated at its optimum efficiency during average periods.

With some prime movers, energy can be stored in some form (such as waterhead, heat, or pressure) to be used during peak periods. It is also possible to store electrical energy with batteries or other storage cells, or to manufacture hydrogen during off-peak periods for use in fuel cells when the demand is high. In some instances, such as in switchgear, engine starting, and small motors, direct current may be used without inversion; however, most uses would require alternating current so that an inverter or motor generator is necessary.

There are several ways to obtain estimates of peakloading for households; for example, from National Electrical Code data or National Association of Home Builders data, or by using the standardized or derived curve methods. Many factors must be considered in using the values obtained by these methods so that they will apply to all situations. In some instances, for normal dwellings, the peak may be only 10 percent larger than average, and in others the peak may approach 70 percent. Load factor considerations based on size, cost, location, et cetera, will be among the predominant factors affecting MIUS operations.

Control Systems

A control system governs or regulates functions in a predetermined sequence. Controls may be manual, semiautomatic or automatic, solid state, electrical, or pneumatic. As applied to devices such as motors, control functions include starting, acceleration, speed, power, protection, reversing, jogging, and stopping. In total energy central control systems, each of the various categories may be found. Many companies specialize in electrical controls, and most designs reflect cost-conscious engineering.

Cost, availability, reliability, and power requirements are some of the factors that must be considered in the selection of a method of control. The semiconductor industry has made such great strides in logic circuitry that, for most complex logic control functions, this is the only acceptable approach. The use of relays for much of the same type logic is still very prevalent because of their characteristic advantages.

The MIUS concepts require that operation be made as automatic as practical. Phasing of generators, load shedding, load acquisition, switchover to backup and emergency modes, and overload or fault isolation are all areas in which full automatic control is readily available. The full automatic operation of very complex operations is possible through the use of a minicomputer-type central control system and local control manipulations.

Even the simplest total energy installation requires many controls whether the system is manual or automatic. Some of the easily identifiable areas for a single-unit system would be engine speed and stop-start, fuel supply (flow and quantity, preheating, engine protection, generator regulation and protection, phasing, and backup circuits such as batteries. The variety of techniques involved for each of these areas precludes detailed discussion here; however, subsystems control coordination for MIUS is very apparent.

APPLICATION DATA

This section describes the existing total energy sites in the United States, the types of power generation used, and approximate costs. Sources for generation equipment ranging from 3 to 100 000 kilowatts are discussed. The NASA experience with these various systems is tabulated, and MIUS candidates are selected.

Total Energy Sites

There are more than 400 on-site or total energy installations in the United States today. The Urban Systems Project Office personnel have visited more than 20 of these sites, some of which have been completed and some of which are still under construction. Some of the sites that were visited are listed in reference 3. The installed kilowatt capacity for the sites visited is also shown in reference 3. A summary of the installed kilowatt capability and the number of total energy sites in the United States is given in table V. This chart also shows the kilowatt range of each type of power generation system. The fuel cells, liquid-metal Rankine cycle, and the organic Rankine cycle systems are not considered available. For applicability of these systems to MIUS, further research and development would be necessary. Most of the total energy projects today use primarily natural gas reciprocating internal combustion engine/generator sets, as shown in table IV. Diesel engines, gas turbines, and steamplants are used by the remainder.

Available Power Generation Equipment

A listing of available power generation and electrical energy storage systems covering the power range of 30 to 100 000 kilowatts is given in table VI. Typical cost and fuel consumption data are also given. The interconnecting relationships between components of the power generation subsystem and some perspective to the interdependence of the various power generation components is shown in figure 11.

CONCLUDING REMARKS

Obviously, many electrical power generation systems can be eliminated as candidates for the MIUS prime electrical power system. The MIUS is intended for use throughout the United States in remote areas as well as intercities; therefore, tidal, geothermal, hydroelectric, and wind systems are not acceptable. Solar photovoltaic and solar concentrator power generation cannot be used for near-term MIUS applications because of the size and modularity requirements of MIUS. Magnetohydrodynamics, thermionics, and thermoelectric systems are eliminated because of unavailability in the required power range. These systems cannot be considered for prime power but may be investigated for supplemental power.

The following systems will be investigated both singularly and in parallel for use as the prime power source for the MIUS project: steam and organic Rankine cycle systems, open and closed cycle gas turbines, diesel and natural gas engine/generators, and fuel cells. Batteries will be considered as an energy storage device, together with hydrogen/oxygen generators (water electrolysis) and heat storage devices.

Some criteria or factors that will be used in the selection of prime, parallel, and supplementary power sources for the MIUS are as follows.

1. Cost: capital and operational

2. Development status: state of the art, development risk (including all components)

3. Performance: conversion efficiency, energy use

4. Reliability

5. Maintainability

6. Volume requirements

7. Safety considerations: high-pressure toxicity and explosive potential

8. Resources conservation

9. Environmental pollution: air, water, noise, and land

10. Growth potential and flexibility

11. System complexity

12. System life: time between overhauls

13. Resource availability: fuel, supply, wind conditions, solar energy availability

14. Plant site considerations

15. Power conditioning/distribution requirements

16. Other criteria peculiar to specific application

The various components of a power generation system have been discussed and prime candidates indicated. These individual items cannot be specified until the interface relationships have been established by performing system engineering designs.

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National Aeronautics and Space Administration
Houston, Texas, November 30, 1973
386-01-00-00-72

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TABLE I.- ADVANTAGES AND DISADVANTAGES OF WATER, METALS, AND ORGANICS AS WORKING FLUIDS

Working fluid	Advantages	Disadvantages
Water	Low cost; easy availability; nontoxic, relatively high efficiency of cycle	Necessity for carefully controlling corrosion during operation
Organics	Can be used for low-temperature operations for extracting work from low-level heat; no corrosion	Relatively low thermal efficiency because inlet temperatures must be limited to prevent breakdown of fluid, which results in sludging of system
Metals	Very high thermal efficiency (45 to 50 percent) when used as a topping cycle in a binary operation	Technology not completely off-the-shelf; toxicity problems (mercury); explosion problems in binary cycle with water

TABLE II

diesel engines

manufacturers	2/4 stroke	*cont rating bhp	engine speed rpm	bore/stroke mm	nr of cyls line or v	turbo charging	air charge cooling
Bolnes - Krimpen a/d Lek	2	450- 1500	500- 600	190/350	3-10 L	yes	yes
Brons - Appingedam	2	100/ 400	320- 375	220/380	2-3-4-5-6 L	no	no
	2	375- 2000	250- 375		6-8-12-16 V	yes	yes
Industrie - Alphen a/d Rijn	4	80- 320	750	200/270	2- 8 L	no	no
	4	318- 424			6- 8 L	yes	no
	4	360- 480			6- 8 L	yes	yes
	4	450- 600			6- 8 L	yes	yes
	4	540- 720			6- 8 L	yes	yes
	4	330- 440	500	250/350	6- 8 L	no	no
	4	510- 680			6- 8 L	yes	no
	4	600- 800			6- 8 L	yes	yes
	4	750- 1000			6- 8 L	yes	yes
	4	510- 680	400	305/460	6- 8 L	no	no
	4	672- 896			6- 8 L	yes	no
	4	750- 1000			6- 8 L	yes	yes
	4	930- 1240			6- 8 L	yes	yes
	4	1050- 1400	430		6- 8 L	yes	yes
	4	850- 1150	300	400/600	6- 8 L	no	no
	4	1140- 1520			6- 8 L	yes	no
	4	1350- 1800			6- 8 L	yes	yes
	4	1560- 2080			6- 8 L	yes	yes
	4	1800- 2400	320		6- 8 L	yes	yes
Royal Schelde - Vlissingen	2	7500-16500	137- 150	680/1250	5-10	yes	yes
	2	10000-20000	122	760/1550	5-10	yes	yes
	2	17400-34800	122	900/1550	6-12	yes	yes
	2	32000-48000	108	1050/1800	8-12	yes	yes
Smit & Bolnes - Zierikzee	2	1200- 9700	250- 375	300/550	5-10L/10-20V	yes	yes
Stork-Werkspoor Diesel - Amsterdam	4	180- 270	1000-1200	150/225	6- 8 L	no	no
	4	245- 360			6- 8 L	yes	no
	4	275- 400			6- 8 L	yes	yes
	4	190- 300	1200-1500	150/210	6- 8 L	no	no
	4	300- 445			6- 8 L	yes	no
	4	360- 525			6- 8 L	yes	yes
	4	330- 510	720- 900	210/300	6- 8 L	no	no
	4	515- 750			6- 8 L	yes	no
	4	635- 920			6- 8 L	yes	yes
	4	865- 1500	750-1000	240/260	6- 9 L	yes	yes
	4	3800-13000	500- 550	410/470	6-9L/10-20V	yes	yes

* The ratings in this table are subject to increase by development.

TABLE III

survey of all the Dutch diesel engines
latest developments

manufacturers	2/4 stroke	*cont. rating bhp	engine speed rpm	bore/stroke mm	nr of cyls line or v	turbo char-ging	air charge cooling	year of intro-duction
Bolnes - Krimpen a/d Lek	2	1500- 3000	600	190/350	12-20 V	yes	yes	1973
Industrie-Brons - Alphen a/d Rijn Appingedam	2	1000- 5000	500- 600	220/380	6-8-10-12-14-16 V	yes	yes	1974
Smit & Bolnes - Zierikzee	2	550/cyl	428	300/550	5-10 L/10-20 V	yes	yes	1974
Stork-Werkspoor Diesel - Amsterdam	4 4 4	1150- 2000 4000-15000 10000-31000	750-1000 550- 600 400- 428	240/260 410/470 620/660	6-9 L 6-9 L/10-20 V 6-9 L/12-18 V	yes yes yes	yes yes yes	1974 1974 1975

* The ratings in this table are subject to increase by development.

TABLE IV.- SYNCHRONOUS GENERATOR EFFICIENCIES AT 100, 75, AND 50 PERCENT LOAD CAPACITY

kW at an 80-percent power factor	RPM	2400 V 100	2400 V 75	2400 V 50	4160 V 100	4160 V 75	4160 V 50	6900 V 100	6900 V 75	6900 V 50	13 800 V 100	13 800 V 75	13 800 V 50
1000	500 or 514	94.7	94.3	93.3	94.7	94.3	93.3	94.2	93.6	92.3	93.3	92.5	90.8
1250	500 or 514	95.0	94.6	93.5	94.8	94.4	93.4	94.6	94.0	92.7	93.8	93.0	91.3
1500	500 or 514	95.3	94.9	93.8	95.3	94.9	93.8	94.9	94.3	93.0	94.1	93.3	91.6
1750	500 or 514	95.5	95.1	94.0	95.5	95.1	94.0	95.2	94.7	93.4	94.5	93.8	92.2
2000	500 or 514	95.6	95.2	94.1	95.6	95.2	94.1	95.3	94.8	93.5	94.6	93.9	92.3
2250	500 or 514	95.8	95.4	94.3	95.8	95.4	94.3	95.5	95.0	93.7	94.8	94.1	92.5
2500	500 or 514	95.9	95.6	94.5	95.9	95.6	94.5	95.6	95.2	93.9	94.9	94.3	92.7
3000	500 or 514	96.1	95.8	94.7	96.1	95.8	94.7	95.9	95.5	94.2	95.3	94.7	93.1
3500	500 or 514	96.3	96.0	94.9	96.3	96.0	94.9	96.1	95.7	94.4	95.5	94.9	93.9
4000	500 or 514	96.4	96.1	95.0	96.4	96.1	95.0	96.2	95.8	94.5	95.6	95.0	94.4
4500	500 or 514	96.5	96.2	95.1	96.5	96.2	95.1	96.3	95.9	94.6	95.8	95.1	93.5
3500	250 or 257	95.5	95.1	94.4	55.5	95.1	94.4	95.4	95.0	94.2	94.7	94.1	93.0
4000	250 or 257	95.7	95.3	94.7	95.7	95.3	94.7	95.6	95.2	94.5	94.9	94.3	93.3
4500	250 or 257				95.8	95.5	94.8	95.7	95.3	94.6	95.1	94.5	93.5
5000	250 or 257				95.9	95.5	94.9	95.8	95.4	94.8	95.2	94.6	93.7
6000	250 or 257				96.1	95.8	95.1	96.1	95.6	95.0	95.5	94.8	93.9
7000	250 or 257				96.2	95.9	95.3	96.2	95.8	95.1	95.6	95.0	94.0
7500	250 or 257				96.3	96.0	95.3	96.2	95.9	95.1	95.8	95.3	94.5

TABLE V.- ON-SITE PRIMARY POWER GENERATION SYSTEMS AVAILABLE OR IN USE

Energy conversion method	Output ranges, kW (a)							Number of total energy systems installed	Fuel type
	10 to 100	100 to 500	500 to 1000	1000 to 5000	5000 to 20 000	20 000 to 40 000	Over 40 000		
Reciprocating engines									
Diesel	X (1)	X (15)	X (12)	X (24)	X (12)			64	Diesel oil
Gas engine	X (30)	X (129)	X (74)	X (77)	X (13)			323	Natural gas, propane, butane
Steam engine	X								Any fossil fuel
Organic fluid	X								Any fossil fuel
Turbine									
Rankine cycle									
Steam				X	X (5)	X (2)	X (1)	8	Nuclear energy or any fossil fuel
Organic	X	X							Any fossil fuel
Liquid metal									Any fossil fuel
Brayton cycle									Any fossil fuel
Gas (open cycle)	X	X (13)	X (9)	X (31)	X (13)	X (4)	X (3)	73	Gaseous hydrocarbon or fuel oil
Gas (closed cycle, potential availability)			X	X	X	X	X		Nuclear energy or any fossil fuel
Binary cycle									
Gas turbine (steam or organic)		X	X	X	X	X	X		Gas or fuel oil
Liquid metal Rankine (steam)				X	X	X	X		Nuclear energy or any fossil fuel
Electrochemical									
Fuel cells	X [b](30)							30	Hydrocarbons or hydrogen

[a]Number of units in operation are indicated by parentheses; the applicable power ranges are indicated by an X.

[b]Prototype in operation.

TABLE VI.- TYPICAL AVAILABLE POWER GENERATOR AND ELECTRICAL ENERGY STORAGE SYSTEM COST DATA

System	Capacity, kW	Manufacturer	Efficiency or fuel consumption	Cost, dollars/kW	Typical cost of unit, dollars (a)	Type unit
Gas turbine	30	Solar	0.04 cubic meter (10 gal/hr)	547	16 500	Open cycle
Gas turbine	60	Garrett	0.04 cubic meter (10 gal/hr)	Not available		Open cycle, recuperated
Gas turbine	320	Garrett	0.25 cubic meter (65 gal/hr)	281	90 000	Open cycle, recuperated
Gas turbine	2500	Garrett	0.76 cubic meter (200 gal/hr)	Not available		Open cycle, recuperated
Diesel	50	Winco	0.02 cubic meter (6 gal/hr)	137	6 800	Reciprocating
Diesel	100	Winpower	0.03 cubic meter (9 gal/hr)	92	9 200	Reciprocating
Diesel	175	AC	0.05 cubic meter (13.5 gal/hr)	72.5	12 700	Reciprocating
Diesel	500	Onan	0.15 cubic meter (39.6 gal/hr)	82	41 000	Reciprocating
Diesel	2000	Fairbanks/Morse	0.61 cubic meter (160 gal/hr)	50	100 000	Reciprocating
Steam turbine	20 000	General Electric	25 percent	52.7	1 055	
Steam turbine	100 000	General Electric	36 percent	40.4	4 040	
Battery	[b]800	Exide	Not applicable	158	7 600	Lead-acid
Battery	[b]572	Exide	Not applicable	492	17 400	Nickel-cadmium
Fuel cell[c]	5 to 250	Pratt & Whitney		110		Acid electrolyte
Battery	[d]40	Exide & Gould	Not applicable	<1/kWh of rating	140 000	Lead-acid

[a] These estimates are free-on-board from the manufacturer's plant; installed costs are two to three times the figures given.
[b] Ampere-hours.
[c] The fuel cell is not commercially available now.
[d] Kilowatt-hours.

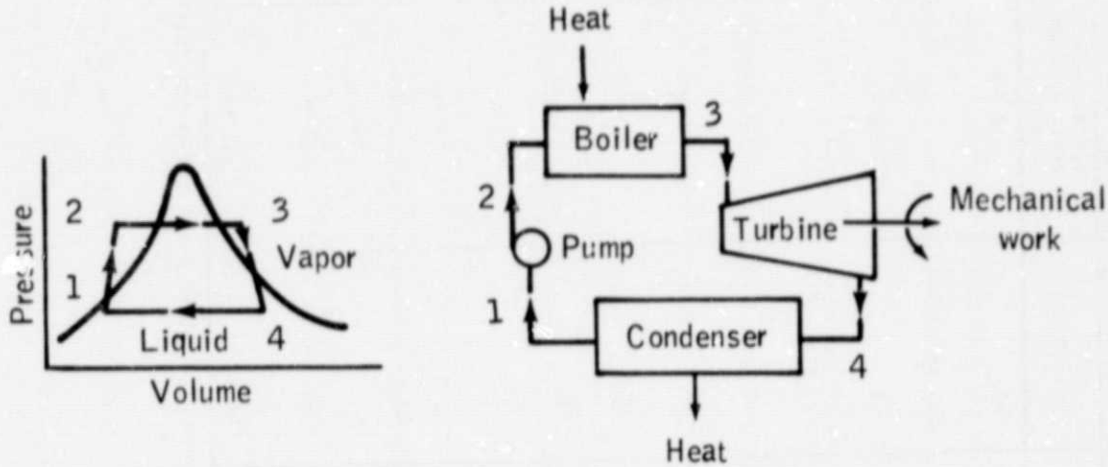

Figure 1.- Simple Rankine cycle.

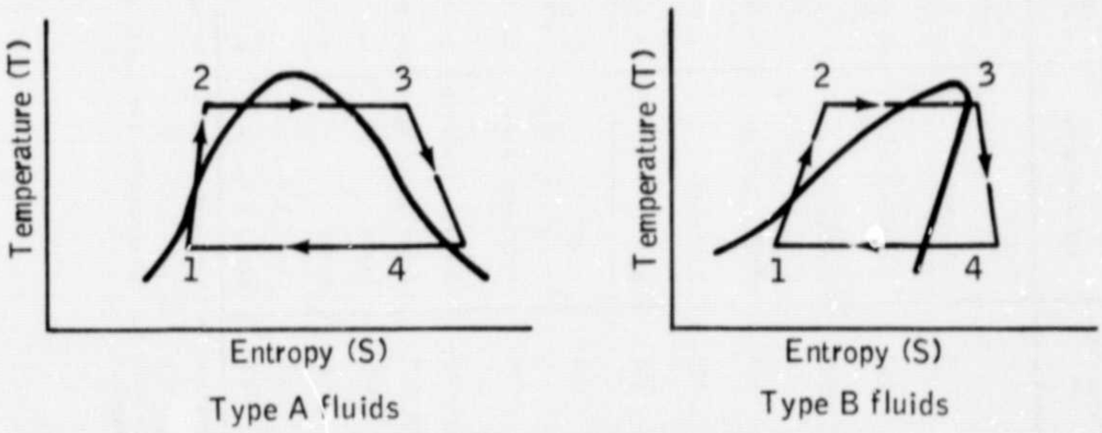

Figure 2.- Rankine T-S diagrams for type A and B fluids.

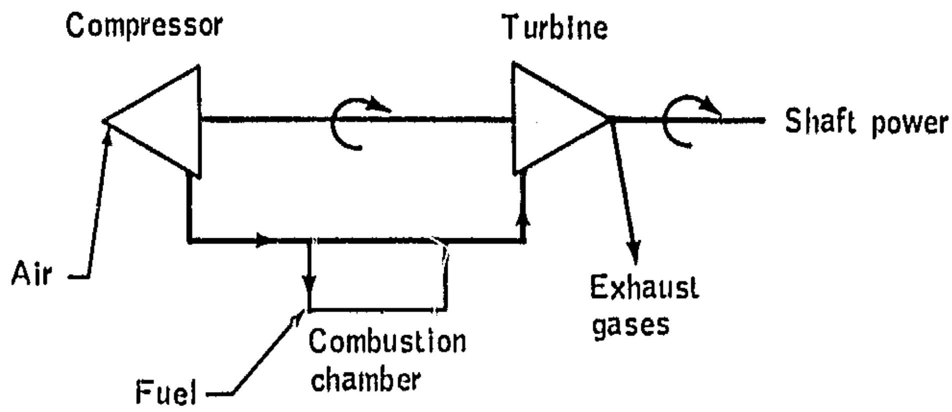

Figure 3.- Simple open cycle gas turbine.

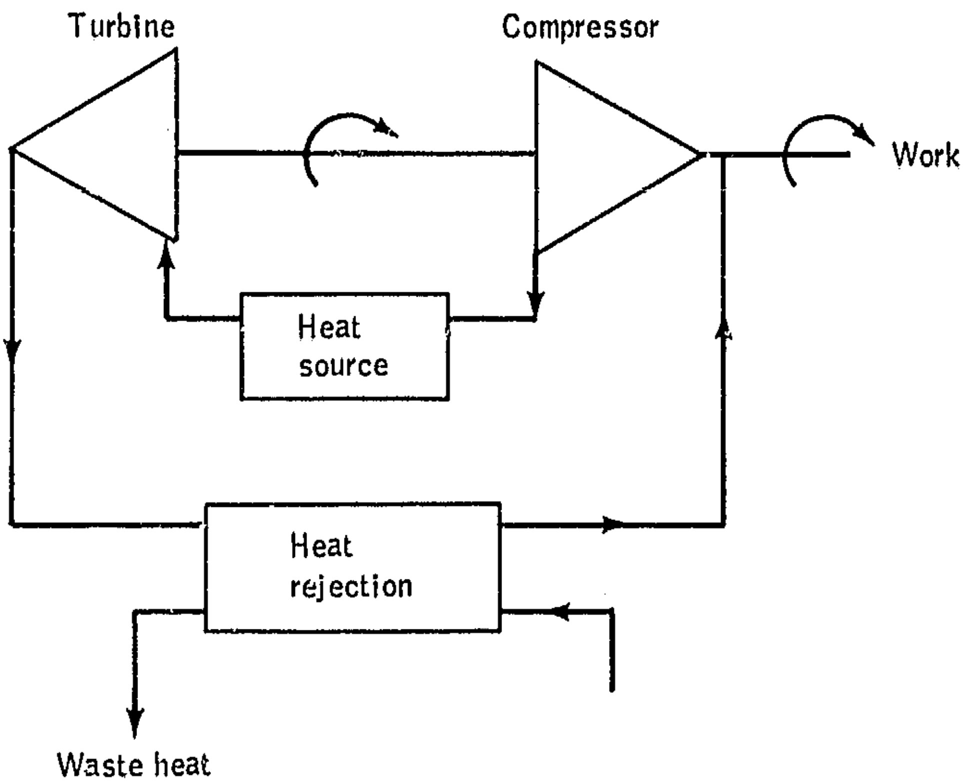

Figure 4.- Simple closed Brayton cycle.

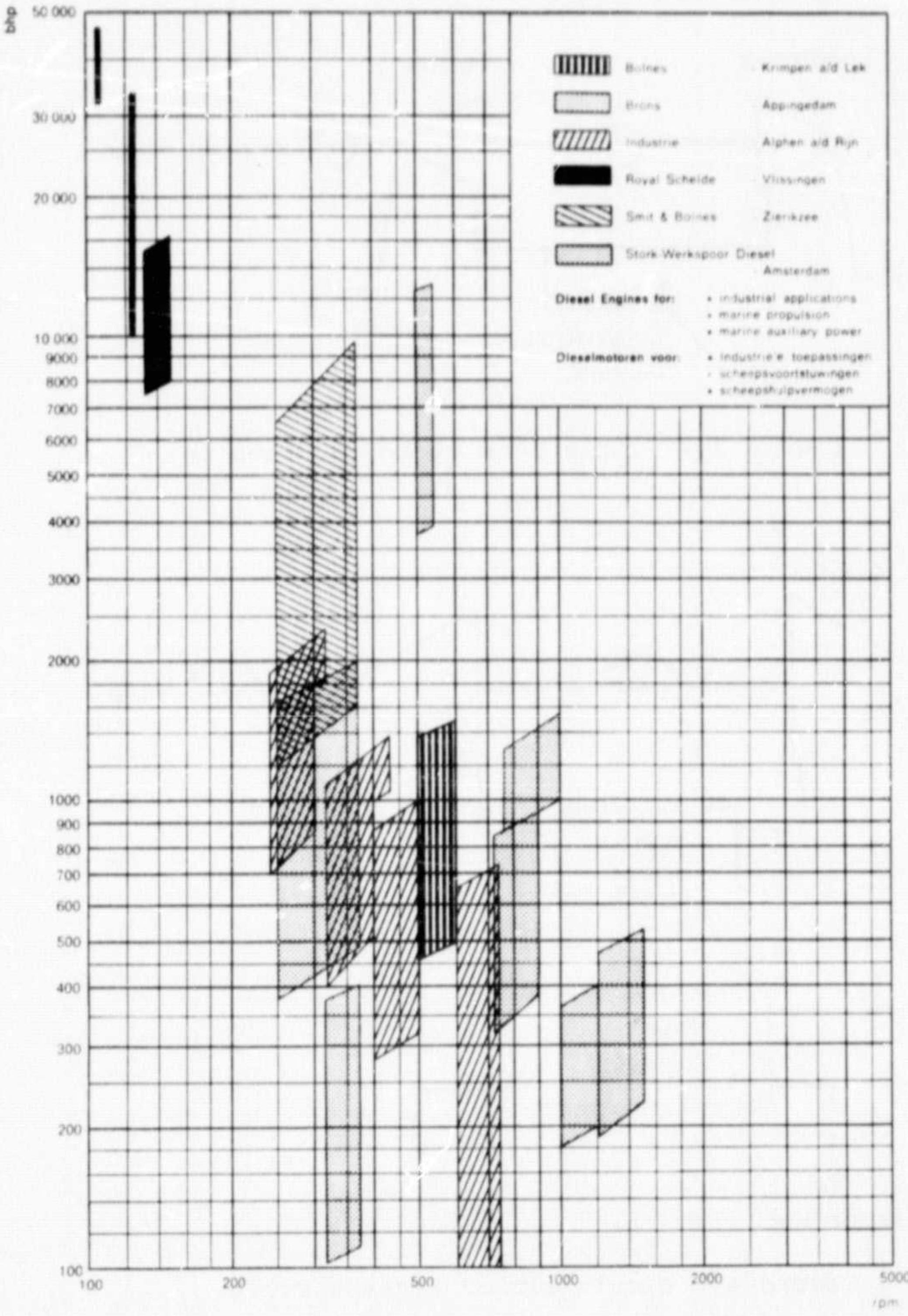

Figure 5.- Dutch diesel engines (brake horsepower versus rpm).

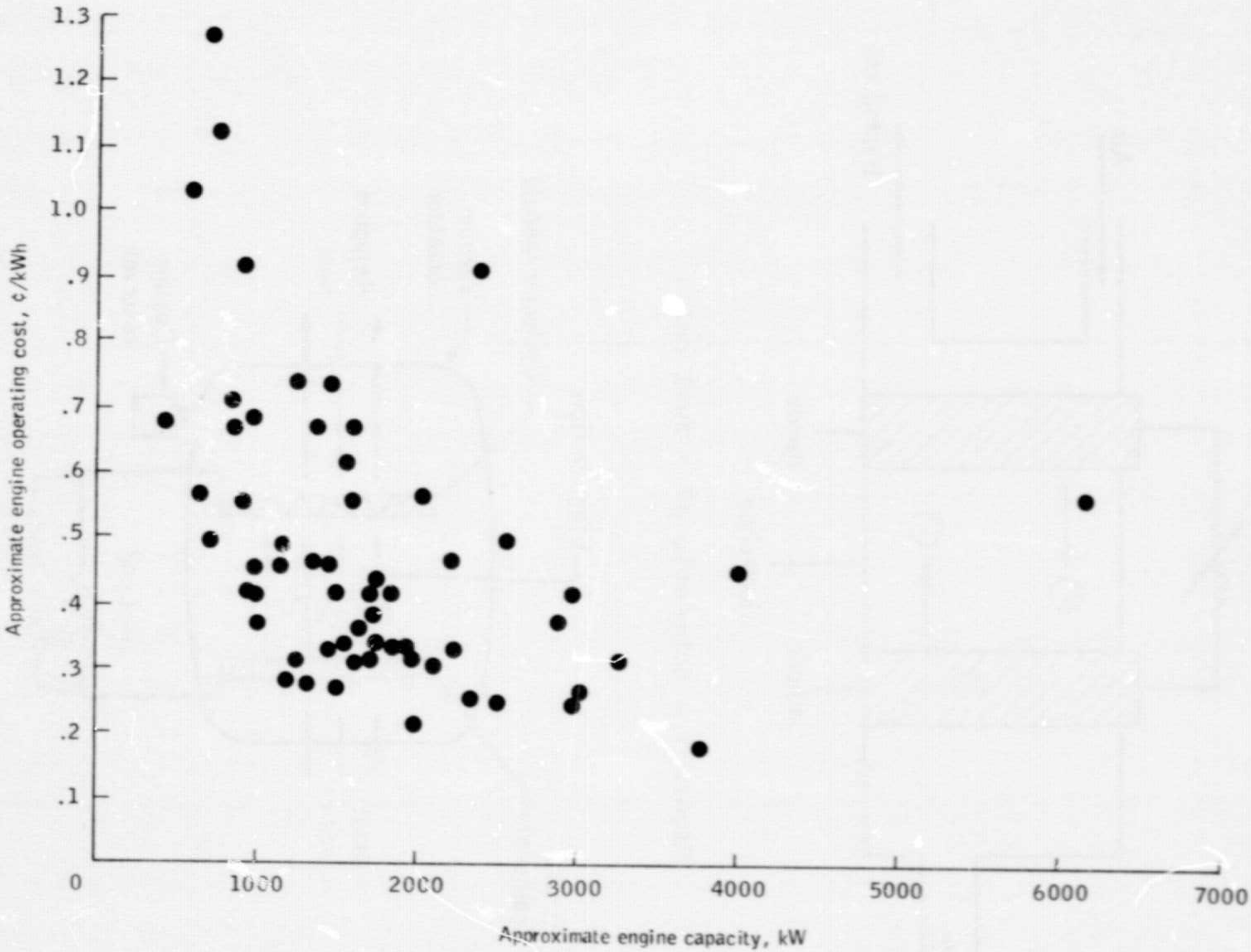

Figure 6.- Engine operating costs as a function of engine capacity.

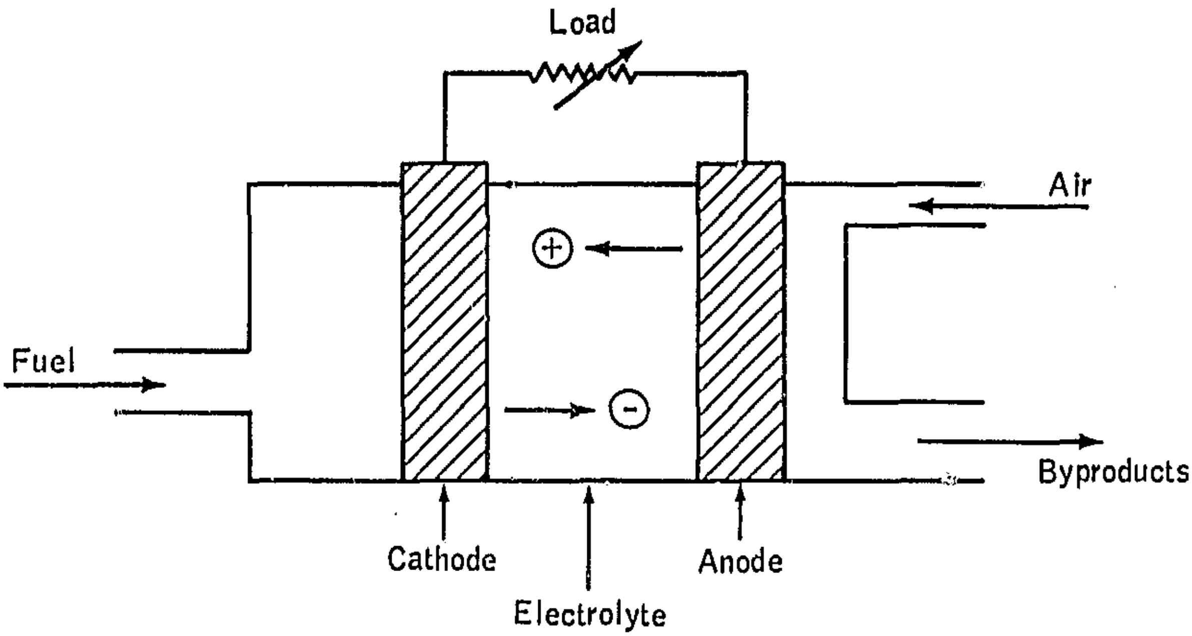

Figure 7.- Schematic of a fuel cell.

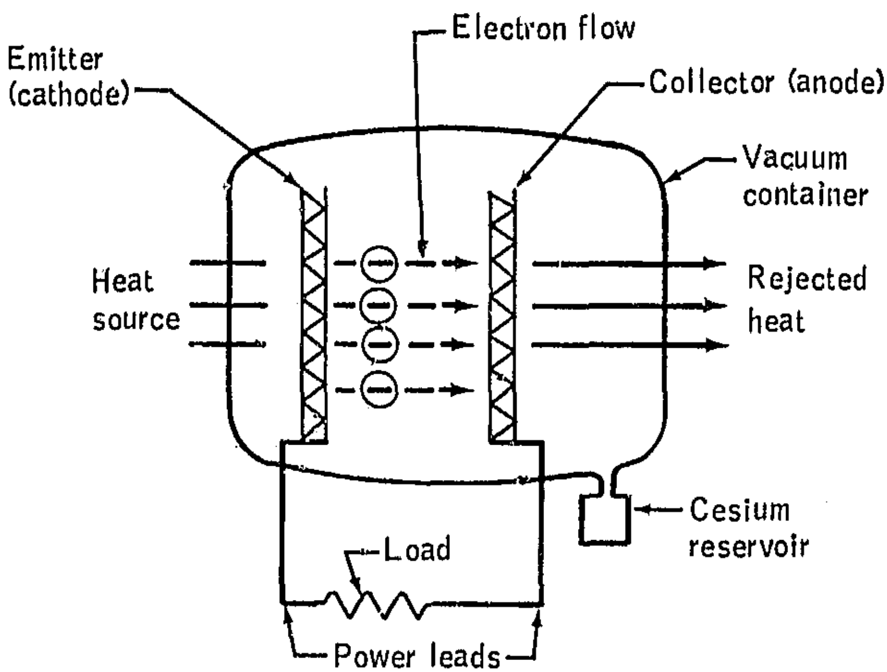

Figure 8.- Schematic of a thermionic energy converter.

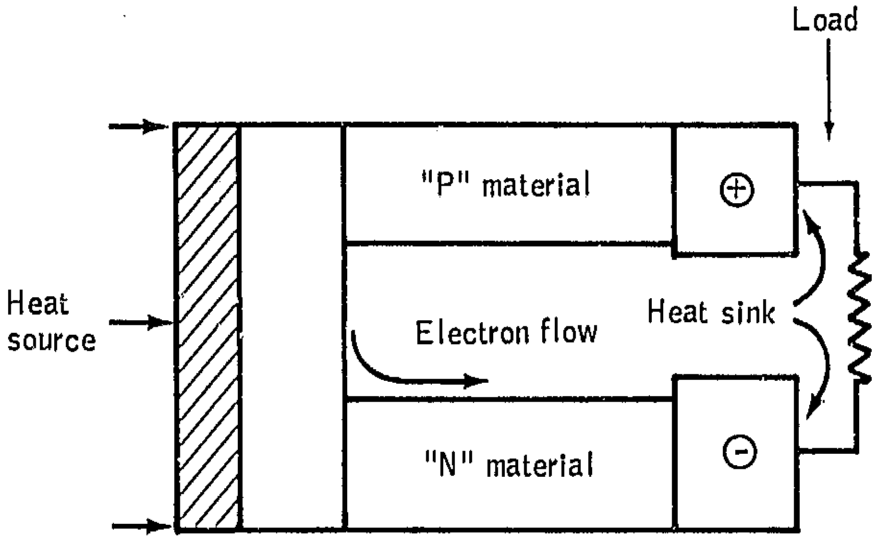

Figure 9.- Schematic of a simple thermoelectric generator.

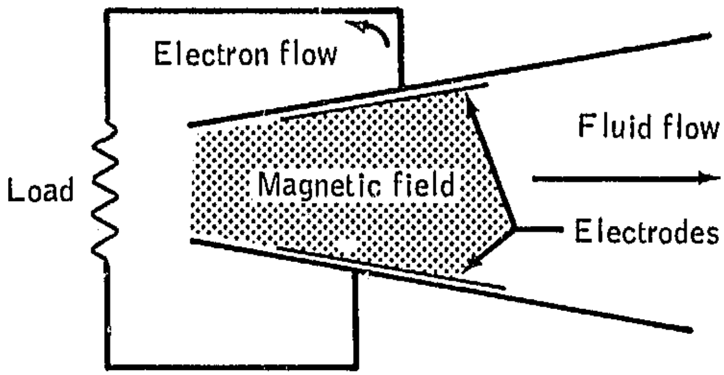

Figure 10.- Schematic of a simple magnetohydrodynamic system.

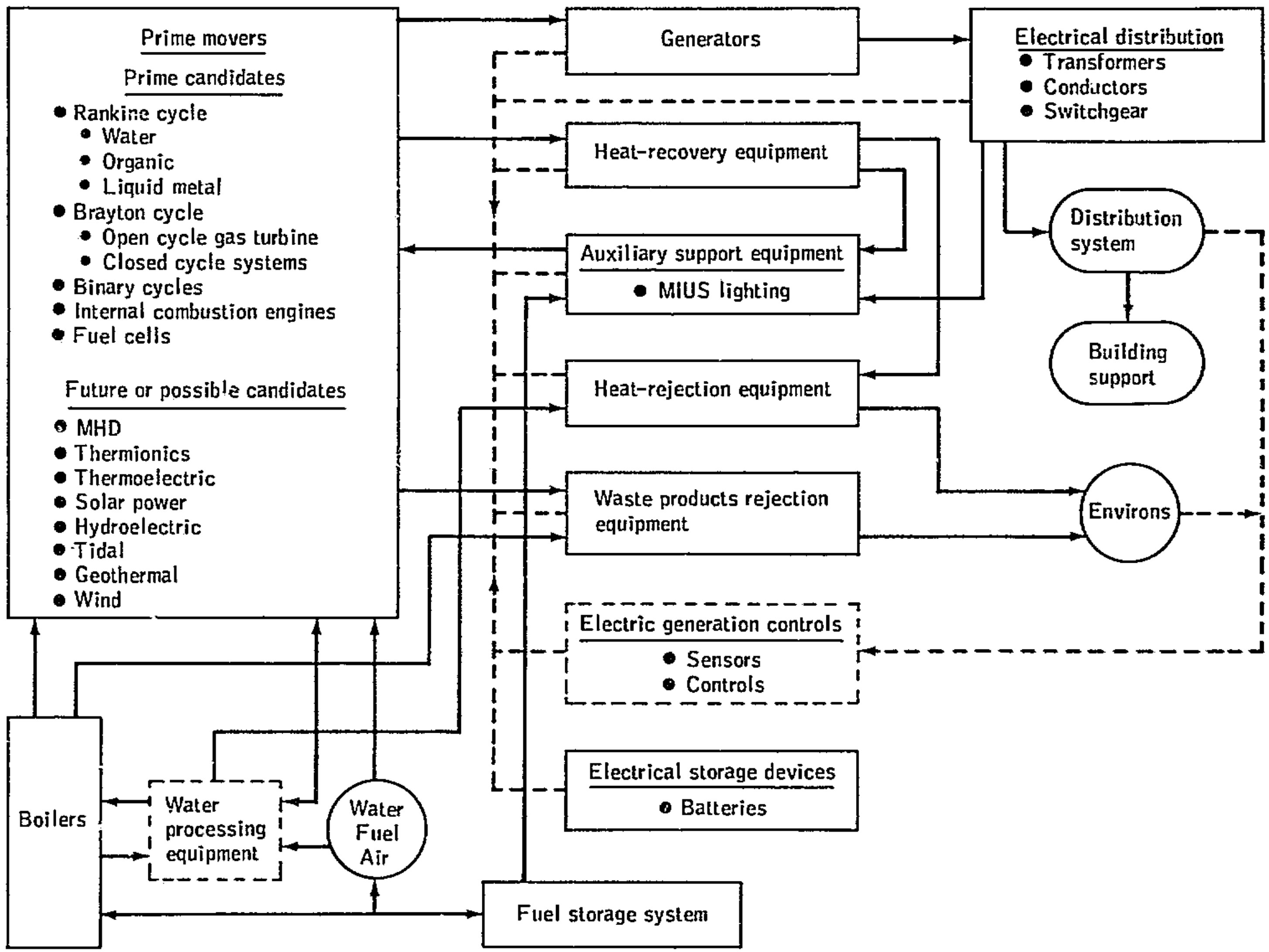

Figure 11.- MIUS power generation equipment.

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